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VOL. LII

CAMBRIDGE, MASS., U. S. A.
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Memoirs of the Museum of Comparative Zoölogy
AT HARVARD COLLEGE
Vol. LII

GEOGRAPHY AND GEOLOGY OF THE REGION INCLUDING CAPE COD, THE ELIZABETH ISLANDS, NANTUCKET, MARTHAS VINEYARD, NO MANS LAND AND BLOCK ISLAND

BY

J. B. WOODWORTH AND EDWARD WIGGLESWORTH

With Thirty-eight Plates

CAMBRIDGE, MASS., U. S. A.:
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1934

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EDITORIAL FOREWORD

The publication of this memoir on the geology of Cape Cod and the New England islands would have been a source of great satisfaction to Prof. Woodworth had he lived. It is a summation of the results of long continued study by him, which was begun many years ago in association with Prof. Nathaniel S. Shaler. In a letter to the junior author at the time he received the request from the United States Geological Survey to write the report, Prof. Woodworth stated, "The long awaited and oft expected has occurred," and suggested the glacial geology of Marthas Vineyard as the subject for a doctor's thesis which could later be revised as part of the report. The present volume is a fitting memorial to Prof. Woodworth in that it is the culmination of his work in one of the lines of study in which he was most interested.

The field work and preparation of the manuscript was originally done for the Section of Coastal Plain Investigations, U. S. Geological Survey, T. W. Vaughan, Geologist in charge. Early in 1920 the manuscript was transferred to the Section of Glacial Geology, Wm. C. Alden, Geologist in charge, by whom it was revised, and preparation for publication was begun. For various reasons, which need not be detailed here, preparation for publication was not completed when Prof. Woodworth died, August 4, 1925.

In 1926, Mr. Samuel Henshaw, Director of the Museum of Comparative Zoölogy and a long time friend of Prof. Woodworth, suggested to me that he would be glad to publish the report, in memory of Prof. Woodworth, as one of the Museum's memoirs, and a proposal was made to the Director of the Federal Survey. Permission to do this was granted by the Director, Mr. George Otis Smith, and the manuscript was turned over to Mr. Henshaw, with the assurance of assistance by the Survey in further preparation. Work on editing and preparation of the plates was commenced at once, but again was not completed at the time of Mr. Henshaw's resignation as director of the Museum. After some delay, owing largely to the fact that certain funds expected for publication were no longer available, the present Director of the Museum, Dr. Thomas Barbour, arranged to have the manuscript reduced in volume and to be further edited by the late George M. Wood, retired editor of the Federal Survey. To the services of Mr. Wood is due in large measure the excellence of the text of the memoir as now issued. To obtain necessary funds to complete the publication, an appeal was made for a grant from the Penrose Fund of the Geological Society of America, which was generously given, thus removing the last obstacle in the way of printing.

In addition to the several changes of plan and the many hands through which the manuscript has passed, there has been the additional difficulty of putting it through the press without the help of the chief author. The finished result, therefore, is not what it otherwise might have been, and more particularly copy for a number of Prof. Woodworth's plates could not be located, a fact which accounts for the incongruous lack of sequence in the plate and map numbers, and their order of appearance. In fairness to Prof. Woodworth it should also be stated that a large amount of valuable material had to be omitted in order to reduce the cost of the report, and the effect of this will be much more obvious than if the original author had been able to adapt the rest of the memoir to these omissions.

Acknowledgement is made to the U. S. Geological Survey for transfers of the engraved topographic maps, and to C. A. Weckerly, Chief of the Section of Illustrations of the Federal survey, who with assistance by O. W. Goodloe, prepared the geologic maps and drawings at the expense of the Museum of Comparative Zoölogy. Valuable assistance was also rendered at various times by Wm. C. Alden, of the Survey, in getting text, maps and illustrations ready for publication, but owing to pressure of other duties Mr. Alden did not have the opportunity to reexamine the manuscript after the revision by Mr. Wood. He did, however, read the entire galley proof, making numerous helpful suggestions, and Dr. L. W. Stephenson, the author of the section, "Collections of Upper Cretaceous Fossils" (of Marthas Vineyard), read and corrected this part of the memoir. The U. S. Coast and Geodetic Survey, R. S. Patton, Director, was so kind as to permit reproduction of certain plates published in their reports to illustrate this memoir. Also thanks are due to Professors Kirtley F. Mather and Kirk Bryan, who very kindly read the whole manuscript in an effort to eliminate any errors, and who made many valuable suggestions. Finally, very sincere thanks are due to Mr. Ludlow Griscom of the museum, for preparing the report for the printer and reading all proof.

EDWARD WIGGLESWORTH

PART I

OUTLINE OF THE GEOGRAPHY AND GEOLOGY OF THE REGION

OUTLINE OF THE GEOGRAPHY AND GEOLOGY OF THE REGION

By J. B. Woodworth

INTRODUCTION

The first part of this report presents a general view of the district surveyed and summarizes the palaeontologic data; the second part describes in detail each particular area considered. Although this method of treatment involves some repetition, it has been employed in order to adapt the matter to the use of the general reader on the one hand, and of the reader who may be interested in a particular area or island on the other.

The field work on which the report is primarily based was done in the summers of 1914 and 1915. Assistance in the field was received from Mr. Gilbert Hart, who deserves particular mention for his work on the Elizabeth Islands, west of Naushon. Many observations that have been utilized were made by me during visits to Cape Cod and the islands, either in connection with the work of the United States Geological Survey or as instructor in geology at Harvard University.

Dr. Wigglesworth studied the geology of Marthas Vineyard at his own expense under my direction, and his original manuscript, of which the accompanying account of the geology of that island is an abstract, was filed in the archives of Harvard University in part fulfillment of the requirements for a doctorate.

Thanks are due to Dr. T. W. Vaughan and to Dr. W. C. Alden for advice and personal consultation in the field concerning some mooted points in the Pleistocene history of the district, and especially to Dr. W. H. Dall for the identification of the marine fossils.

TOPOGRAPHY

Cape Cod is a peninsula composed of gravel, sand, and clay, which extends from southeastern Massachusetts into the sea in the form of a bent arm that encloses Cape Cod Bay. South of Cape Cod there is a group of islands, sometimes called "the New England Islands," which includes Nantucket, Marthas Vineyard, No Mans Land, Block Island, and the Elizabeth Islands. These islands are separated from the mainland and from Cape Cod by navigable sounds. Although Cape Cod at first sight appears to be quite unlike the islands, a close examination shows that it has certain features in common with Marthas Vineyard and Nantucket, and that it is composed of deposits of similar character and origin. The islands and sounds were formed by glacial action in Pleistocene time, when beds of unconsolidated gravel, sand, and clay were laid down by the continental glacier, which then advanced over this region from the north, and by the erosive work of streams. The outer shores of Cape Cod and of Nantucket show where the great frontal moraines of that glacier pass seaward to the submerged fishing banks off the coast. The maximum extension of the great sheets of ice that produced these features is shown in Figure 1.

Some of the formations belonging to the older part of the Pleistocene series are greatly disturbed, and the work of Veatch[1] and of Fuller[2] on Long Island first made known the sequence and the geologic age of certain beds of blue clay in the New England Islands, which can now be separated from beds of dark Cretaceous clay, so that the older Pleistocene deposits can be correlated. In this report Dr. Wigglesworth has made the proper correlation of these beds of clay and the associated beds of sand on Marthas Vineyard. Except for local breaks in their basal part, the Pleistocene beds extend almost continuously from Long Island eastward to Marthas Vineyard.

The topography of Cape Cod and of the New England Islands is predominantly glacial, but some tracts display forms shaped by the action of running water on unconsolidated clay and sand and modified by the action of moving ice. Certain plains and high tracts or ridges, both on Cape Cod and on the islands, present a morainal configuration, but much of the general form of Marthas Vineyard is not distinctly morainal. At many places morainal features are imposed upon an older surface that was not shaped by glacial or stream action. The appearance of morainal origin is due in part to the numerous ice-borne boulders that strew the surface.

Throughout large tracts on Block Island and No Mans Land and in the northern part of Nantucket there is a pseudo-morainal topography due to the kneading and deformation of old stratified glacial deposits by the last ice sheet. No geologic sections are available to show the relation of the form of the surface to the details of the structure beneath, and it is therefore difficult to decide whether the configuration at many places is due to morainal accumulations laid down by the last ice sheet or to the form of older deposits that are covered

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[1] Veatch, A. C., and others, Underground water resources of Long Island, N. Y., U. S. Geol. Survey Prof. Paper 44, 1906.

[2] Fuller, M. L., The geology of Long Island, N. Y., U. S. Geol. Survey Prof. Paper 82, 1914.

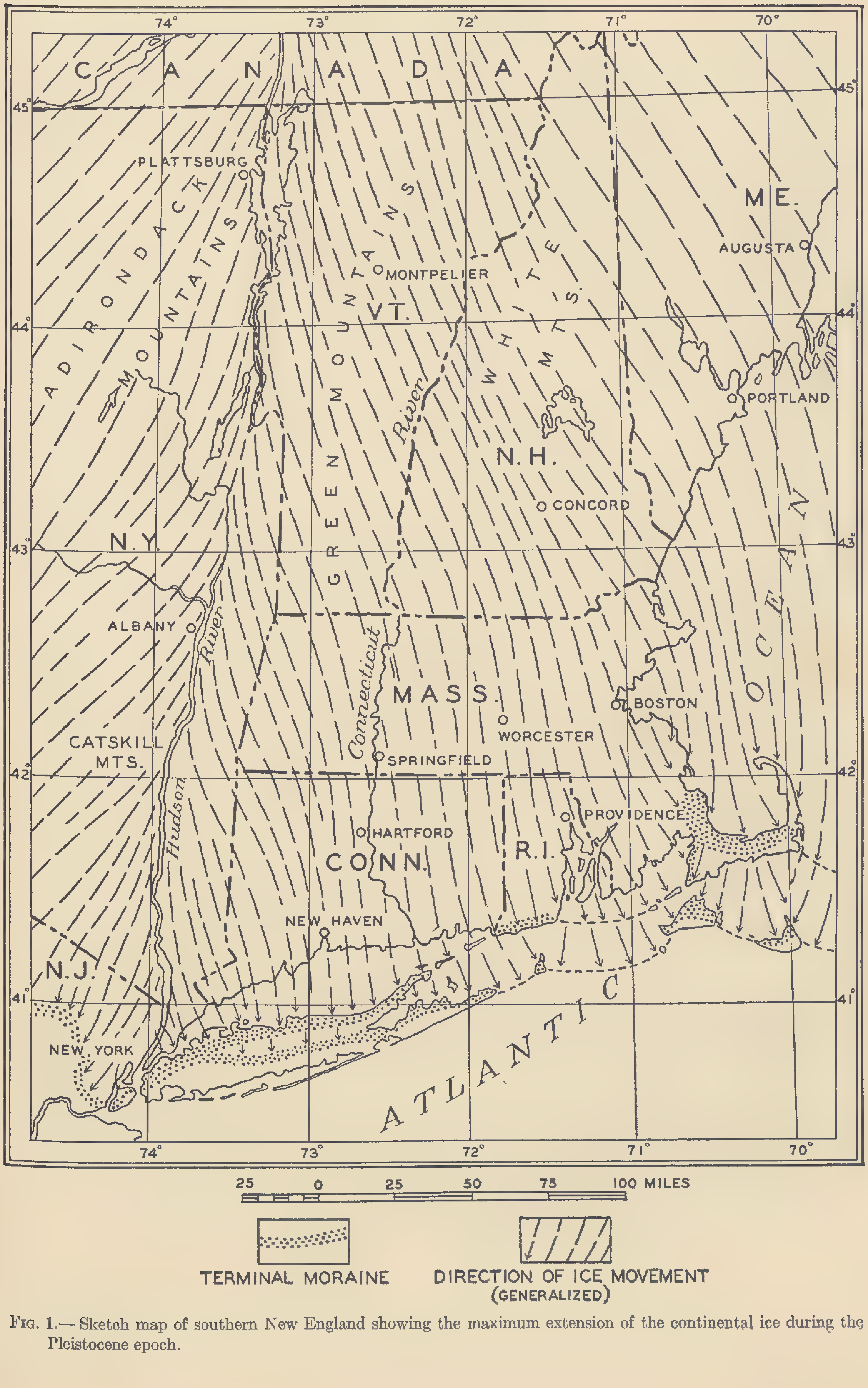

Fig. 1.— Sketch map of southern New England showing the maximum extension of the continental ice during the Pleistocene epoch.

by glacial drift and boulders. It is mainly in the recognition of this wrinkle-moraine or pseudo-moraine and its significance as to the age of the deposits forming the mounds, which are scattered over the surface, that this report represents an advance in the interpretation of the structure and origin of a large part of the morainal belt on the outer islands.

The nearly flat plains on Marthas Vineyard, Nantucket, and Cape Cod, generally underlain by gravel and sand, consist of deposits laid down by streams that flowed out from the ice front, but the plains in certain areas were leveled by running water that flowed over old glacial deposits. Cliffs shaped by the erosive action of sea waves in sand, gravel, clay, and till are common. The longest stretches of these cliffs are found on the east side of Cape Cod, where they extend from Highland Light southward beyond Chatham. Other well-marked lines of cliffs stand along the south side of Marthas Vineyard, in Chilmark; at the west end of that island, at Gay Head; on the south side of No Mans Land; and on the south side of Block Island. The southward-facing cliffs are composed mainly of dark clays and old boulder beds.

The relief of the district is generally low, in common with that of the Atlantic coastal plain, of which it forms a peculiar part. The land about Cape Cod Bay and on the islands rises slightly more than 300 feet above mean sea level at three points: Manomet Hill, in Plymouth (altitude about 390 feet); Peaked Hill, on Marthas Vineyard (altitude 311 feet); and Prospect Hill, near Peaked Hill (altitude 308 feet). Manomet Hill is wholly of glacial origin, and the two highest points on Marthas Vineyard are drift-capped hills formed by the erosion of deformed Cretaceous and early Pleistocene beds. The highest point on Nantucket is a rounded knob of deformed drift, 100 feet high, in the morainal belt. No Mans Land has one similar high point, which stands at an altitude of 110 feet. One point on Block Island has an altitude of 211 feet, and a small area in the northern part of that island and a large area in its southern part rise above 100 feet.

The topography of the upland and of the till-covered tracts in the northern part of Nantucket, the northern and western parts of Marthas Vineyard, and the whole of No Mans Land and Block Island is the net result of the following processes:

1. Deposition of beds of boulders, gravel, sand, and clay on the sand and clay of the coastal plain.

2. Deformation, dislocation, and overthrust by ice during the two or three stages of glaciation prior to the last.

3. Sculpturing of the surface during times when it was exposed to stream erosion.

4. Slight erosion and mantling by thin sheets of drift of the last glacial incursion.

The nearly flat outwash plains that border the moraines rise from near sea level to an altitude of about 100 feet on Marthas Vineyard and about 60 feet on Nantucket. Their gentle southward slopes bear well-defined creases, which become deeper and wider southward, suggesting channels that were once occupied by running streams.

The relief of Cape Cod is due in part to action similar to that shown on Nantucket and Marthas Vineyard, and the beds that stand above sea level have been exposed to the action of the same agents of deposition and erosion that were in operation on these islands. A belt of morainal topography of the knob and basin type, without bordering outwash plains, is seen in the Elizabeth Islands. This morainal belt is traceable on the mainland from the southwestern heel of Cape Cod, at Wood's Hole, north-northeastward to the Cape Cod Canal, from which it extends eastward in the form of a rounded, hilly ridge along the south shore of Cape Cod Bay, gradually declining in elevation until, near the east coast, its features merge into those of glacial plains. South of this morainal belt a glacial outwash plain forms most of the surface, the striking features of which are numerous pits and glacial lakes. This outwash plain rises toward the northwest in an interlobate angle between the morainal belts in the form of a large outwash fan, which reaches an altitude of 220 feet above the sea at its junction with the line of glacial deposits that were laid down directly at the front of the ice sheet.

The surface of Cape Cod from the vicinity of Orleans northward may be divided into three tracts, which include glacial plains, though in the middle tract deep kettles and the glacial channels known as "hollows" mask the features of the plain. The northern and the southern tracts stand 60 to 70 feet above sea level and decline gently westward, toward Cape Cod Bay. The middle tract, which rises toward the outer coast, exceeds 100 feet in altitude in much of its area, reaching at some places an altitude of 140 feet. It forms the wildest and most picturesque part of the outer shore of the Cape, which presents to the storms of the Atlantic high bluffs of yellowish gravel and sand.

The outstanding projections in the surface of the Cape and of the islands south of it mark the sites of great terminal moraines, which are traceable westward to New York City and eastward to the coast of New England. Nantucket and Cape Cod extend into the sea to points reached by the ice sheets, whose fronts were aligned from east to west. The great submarine banks off the east coast represent similar features, but their surfaces have been highly modified by the action of waves and current.

In broad outline, the region here considered is formed of two great series of lobate frontal moraines, between the inner and outer lines of which lie Nantucket and Vineyard sounds, and back of the inner line of which, in depressions like those of the sounds in origin, lie Buzzard's and Cape Cod bays. In this festooned distribution of the land the moraines define the outer border of lobes of the ice sheet, formed along paths of the most rapid motion of the ice, the maximum rate of flow of which in each lobe occurred along a line that was directed southward and that lay near the central axis of the lobe. The interlobate moraines, represented by the arm of Cape Cod in Wellfleet and Truro on the one hand and by the Plymouth moraine on the other, were places of minimum rate of flow of the ice, and therefore of heavy deposition. These interlobate lines or axes point west of north, toward obstructions to the flow of the glacier. The direction of the glacial striae on the mainland show that the lobe lying in Buzzard's Bay and in the country somewhat west of it moved along the Merrimac Valley in New Hampshire, and that the lobe lying in Cape Cod Bay moved along a line east of the Mount Washington range, which, together with the Blue Hills of Milton, appears to have been the chief cause of the slack ice motion represented by the Plymouth interlobate moraine. A like relation is traceable in the Wellfleet interlobate axis to Mount Bigelow, in Maine. Still farther east another interlobate axis is faintly suggested in George's Bank, which lies beneath the sea nearly in line with Mount Desert and Mount Katahdin, in northern Maine. The outline of the Cape and of the islands shaped by glacial action is thus a geographic reflex of lines of depression and elevation in the country to the north.

Cape Cod and the outer islands south of it contain few streams, because the porous gravel and sand permit rain water to sink nearly if not quite to sea level. The height of the water table in the plains is shown by the surface of numerous lakes and ponds. An extensive seepage of the water takes place along the coast at points between the levels of high and low tide.

The streams of the islands are limited to areas where deposits of clay occur, as in the upland, western part of Marthas Vineyard. On the south side of the Cape, in Barnstable, the overflow of lakes forms small brooks, which, however, flow in channels cut by the much larger streams that were fed by the melting ice during the last stages of the glacial epoch. Mashpee River is the largest stream of this class.

The lakes or natural ponds on Cape Cod lie in depressions left in glacial deposits by the melting out of large blocks of ice. From their shapes, dimensions, and alignment it is possible to restore a picture of the ice as the glacier approached its final stage. These ponds are particularly numerous in the plains on the south side of the morainal belt on Cape Cod. They are enclosed by steep-sided banks of sand and form great natural wells in the enclosing glacial material. Numerous shallower depressions of like origin also occur in the region, but these are dry, because their bottoms stand above the level of ground water. The depth of the deepest of these ponds, as shown by soundings, is 81 feet. Many small, shallow ponds that formerly appeared on maps have been drained or filled and converted into cranberry bogs.

The coast line of Cape Cod and of the islands has for long stretches been straightened by the attack of the sea, but some of the indentations of the coast near headlands have been protected from such attack by the natural construction of offshore bars and beaches, which are attached at one end to the cliffs that afford the gravel and sand for their construction and maintenance. The indentations of the coast line, the larger of which form small harbors or ports of refuge against certain winds, are nearly all of glacial origin.

Along most parts of the Atlantic coast tidal currents sweep away rapidly the gravel, sand, and clay that are loosened from the cliffs by the waves of storms. The shoals about Nantucket and southeast of Cape Cod are famous for their ever-shifting sand.

GENERAL GEOLOGY

Some account of the geologic formations of the mainland of Massachusetts and Rhode Island is necessary to show the source of the boulders and other glacial erratics that are so widely distributed on the islands off the south coast of these states. For the same reason the boulders on Cape Cod require an account of the geology of the east coast of Massachusetts and the country farther northeast. Much of the gravel, sand, and clay that constitute the deeper formations of the islands and of Cape Cod has been derived from the rocks of the mainland. The geological formations underlying the Upper Cretaceous beds that form the lowest stratum found on the islands and on Cape Cod are here called the pre-Cretaceous basement.

PRE-CRETACEOUS BASEMENT

Throughout the mainland of southern New England the geologic formations that lie beneath the glacial drift and beneath a few exceptional areas of soft beds of Miocene age, such as those at Gay Head and in the town of Marshfield, Mass., are ancient deformed and displaced sediments into which magmas that formed granite and other eruptive rocks have been thrust by several intrusions. The last cycle of geologic change, the effects of which are still evident, was characterized by erosion which produced widespread base leveling of the hard ancient rocks of this part of the continent. The best defined surface formed by this erosion is the beveled slope of the harder rocks in this region, whose extension beneath the New England Islands forms the floor upon which the later beds rest in this part of the Atlantic coastal plain. This surface was formed, locally, at least, before the Upper Cretaceous deposits were laid down. The dissected remnants of this surface along the south coast of Massachusetts, Rhode Island, and Connecticut have a seaward mean dip of about 50 feet to the mile between the 100-foot contour line and the 300-foot or 400-foot contour line. The dip increases from the southern coast of Massachusetts progressively westward to the southern coast of western Connecticut, as shown below:

Quadrangle	100-foot contour to	Dip in feet per mile
MASSACHUSETTS		
New Bedford	200	22?
Fall River	300	20?
RHODE ISLAND		
Newport	—	—
Charlestown	300	32
CONNECTICUT		
Stonington	300	33
New London	400	33
Saybrook	—	—
Guilford	—	—
New Haven	400	50
Bridgeport	400	60
Norwalk	300	60
Stamford	500E	45
Stamford	500W	72

The space between the shore and the mean position of the restored 100-foot contour line is too much obscured by morainal deposits or by inlets of the sea to be considered in estimating the slope of rock surface in the greater part of the district. The increasing inclination toward the west of part of the theoretical old floor on which the Upper Cretaceous beds are believed to have overlapped upon the mainland for at least from 5 to 10 miles inside of the present shore line indicates a steepening warp of the old surface westward. The inclination on the east is nearly that at which strata are laid down on a plain. Farther inland, above the mean position of the outermost points on the land having an elevation of 500 feet, the slope varies widely from the angles indicated by the measurements given, being steeper along certain lines and less steep along others. Thus from central-western Rhode Island the restored contours reveal a steep slope between the 500 and 700 foot contours which extends northward through the Kent, Burrillville, Blackstone, Marlboro, and Groton quadrangles in Massachusetts into New Hampshire. The southeastern versant of the upland west of this slope, which declines southward from the high ground about Worcester, has an altitude of 800 feet in the southwest corner of the Burrillville quadrangle, in Rhode Island. The slope from this point southward to the position of the 100-foot contour is about 22 feet to the mile; thence northward over the upland the land rises at about half that rate to the base of the monadnocks on the Worcester plateau.

From the eastern halves of the Groton, Marlboro, Blackstone, Burrillville, and Kent quadrangles or, in general terms, east of meridian 71° 35 W., no rocky summits rise above 500 feet, except Nobska Hill in the Franklin quadrangle, and the Blue Hills of Milton, south of Boston, in the Dedham quadrangle. Remnants of an old eroded surface that stood between 400 and 500 feet above sea level extend eastward across the Franklin quadrangle and include small areas in the southwestern part of the Framingham quadrangle, in the northwestern part of the Providence quadrangle, and in the Dedham quadrangle. The gabbro hills of Sharon and the Blue Hills of Milton are residual masses that mark the outer limits of this old surface. One small point of rock in the northeastern part of the Franklin quadrangle, near Concord, is also a remnant of this surface. Northeast and southeast of the 400-foot generalized contour there is a broad extension of the coastal lowland of Massachusetts in which the summits rise to 300 feet in the Salem quadrangle and in the Fall River quadrangle. Between the traces of this 300-foot line and the present shore line the descent is much steeper than it is between the 400-foot line and the 300-foot line.

The topographic features of the mainland west of Cape Cod have been described by Davis [1] and later by Keith,[2] who states that it falls into four plateau-like surfaces which become successively lower towards the east, and each group forms bays projecting westward into the higher ones. As a whole they are immense steps or platforms ascending to the central upland. The highest group

[1] Davis, W. M., Nat. Geog. Mon. No. 9, pp. 269–304, 1895. See p. 273, where the lowland about Boston appears to be regarded as the Cretaceous peneplain sloping eastward toward the sea rather than as a surface produced by erosion below the Cretaceous level.

[2] Keith, Arthur, U. S. Geol. Survey Water Supply Paper 415, pp. 8–23, 1916.

forms a north-south belt across the state next to the upland. It has a fairly uniform width of 6 to 15 miles, and its hilltops range between 540 and 650 feet in altitude. Far from this group, but rising to its level, are the Blue Hills of Quincy and Milton, 500 to 640 feet, and Moose Hill, in Sharon, 560 feet.

The next group forms a very irregular belt of hills between 320 and 380 feet above the sea. These are to be seen mainly around the margins of the river valleys and in the two hill belts northeast of Wrentham and Weston. Next below them is a group of hills, between 220 and 260 feet above the sea, which are scattered over much of the state east of the two higher groups and almost reach the sea in Lynn. On the hills of this group in Lynn and Waltham there is scarcely any glacial drift. . . . The summits of the lowest group range between 110 and 160 feet, and their areas form an irregular network along the coast and up the river valleys.

Across this terraced surface the Buzzard's Bay lobe of the ice sheet swept to Marthas Vineyard in its first advance and to the Elizabeth islands in its second stage. The Cape Cod Bay lobe and the South Channel lobe passed southward outside of the site of Boston Harbor, where the ancient rock surface lies below the platforms above described. A remarkable feature of the sea floor in that region is a depression 99 fathoms deep, which shows that at a distance not more than about 35 miles east of Salem the sea floor drops to a depth of more than 800 feet below the platform (220 to 260 feet) which approaches the sea at Lynn. Thus a strong topographic break outlines the eastern rock-bound coast of the state, the interpretation of which is bound up with that of the platforms of the eastern lowland, the date of whose origin is not clearly known. Both of these areas formed the inner margin of the glacially altered coastal plain on the south. Cape Cod and Nantucket belong mainly to the submarine tract, and the islands to the west belong to the eastern lowland.

The eastern lowland cannot be a down-warped part of the surface of the upland, for the south coast, whose intersection with the sea is formed by the mid-Cretaceous erosion plain, has no corresponding offset to the north along the line of flexure which would have been thus introduced. The lowland appears to have been well opened out by Miocene time, for offshore deposits of this age occur at Gay Head and on the borders of the lowland at Marshfield, and the Miocene deposits contain no débris that would have been laid down on the sea floor by the erosion of the surface from the higher to the present level. The surface therefore appears to have been produced between the end of the Cretaceous period and the local beginning of Miocene deposition. An Oligocene date appears most probable.

Cretaceous System

(See Plate 4)

The beds of lignitic clay and the associated beds of white and mottled clay on Marthas Vineyard were assigned to the Cretaceous system in 1890 by David White, who identified certain fossil plants found in them at Gay Head, in the western part of that island. He states that "the flora indicated an age certainly Cretaceous, and probably middle Cretaceous, for the terrane in which it was deposited." [1]

Just before White identified these plants Shaler [2] announced the discovery, in the eastern part of Marthas Vineyard, of angular fragments of a coarse sandstone, which were at many places embedded in the morainal deposits and which had apparently not been transported more than a few hundred feet. Moreover, near Indian Hill blocks of sandstone were associated with tilted beds of unconsolidated sand that were regarded by Shaler as of the same age. In his opinion the Cretaceous beds were limited to a small area that was surrounded by beds of Tertiary clay. Fossils found in the sandstone indicated that the beds containing them were not later than middle Cretaceous.

The fossil plants identified by White had before been regarded as possibly Tertiary in age, and in view of the restriction of the recognizable Tertiary beds (Miocene and Pliocene) at Gay Head to a few feet of greensand and other sand, it became evident in 1889 that the beds of white sand and the associated beds of clay, of various colors, as well as the beds of lignite at Gay Head and elsewhere on Marthas Vineyard, are members of the series of Cretaceous deposits exposed at Perth Amboy and other places on the Atlantic coastal plain.

Dr. Arthur Hollick, continuing the investigation of the leaf-bearing clay beds begun by White, discovered an extension of these beds on Nonamesset Island [3] and correlated these leaf-bearing beds with beds found farther west, on Long Island and Staten Island.[4] As a result of later studies at Gay Head, Hollick [5] writes:

> The stratigraphic relations of the various beds represented in this section are too uncertain for definite conclusions on account of the tilting and distortion to which they have been subjected; but inasmuch as 103 species of fossil plants, a large majority of them representing well-known Cretaceous types, have been identified from this locality alone, the age of the beds from which they came cannot be questioned. Both the Raritan and the Cliffwood (Magothy) formations are represented in these species.

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[1] Am. Jour. Sci., 3d ser., **39**, pp. 93–101, pl. 2, 1890. Also Bull. Geol. Soc. Amer., **1**, pp. 554–555, 1890.

[2] Bull. Mus. Comp. Zoöl., **16**, pp. 89–97, pls. 1, 2, 1889.

[3] Annals New York Acad. Sci., **13**, pp. 387–418 (especially p. 394), 1901.

[4] The Cretaceous flora of southern New York and New England, U. S. Geol. Survey Mon. 50, pp. 27–28, 1906.

[5] *Op. cit.*, p. 27.

The flora of the Cretaceous beds of Marthas Vineyard was still later diagnosed by Berry,[1] who referred the leaf-bearing beds to the Magothy formation in the following terms:

> The upper Cretaceous flora of Marthas Vineyard is extensive, comprising 117 recorded species and coming from three localities (Chappaquiddick, Nashaquitsa, and Gay Head), the bulk of the material coming from Gay Head. This flora has been elaborated by David White and Arthur Hollick. The latter author considered it equivalent to the Raritan formation of New Jersey, but it is obviously younger and equivalent to the Magothy formation. Fifteen of the recorded species are confined to Marthas Vineyard. Of those having an outside distribution, 67 are not found in the Raritan, and of the 35 forms that occur in the Raritan, 29 are also common to the overlying Magothy, leaving six peculiar forms, and these are all vague or unique specimens (*Carpolithus, Williamsonia, Tricarpellites, Tricalycites*). Nearly all of the Marthas Vineyard plants that occur outside of that area are common to the Magothy of New Jersey or Maryland or to post-Raritan formations elsewhere. Thus 44 species occur in the Magothy and 20 are peculiar to Marthas Vineyard and known Magothy, so that I have no hesitation in correlating the leaf-bearing Cretaceous of Marthas Vineyard with the Magothy formation.

The classification of the Cretaceous beds of the Atlantic coastal plain in areas where they have been undisturbed by glacial action has been fairly well determined, and the geologic relations of the plant-bearing beds in the New England Islands can be stated in terms of the formations discriminated in New Jersey and Maryland. In the gulf region the Lower Cretaceous or Comanche series is represented by marine deposits, but on the Atlantic coast it is represented by nonmarine deposits, the northeastern beds of which belong to somewhat later stages of deposition. Thus the Lower Cretaceous deposits of Maryland, comprising the Patuxent, Arundel, and Patapsco formations, here named in ascending order, disappear northward through the gradual transgression of the Arundel and the Patuxent by the unconformably overlying Patapsco formation, and this in turn disappears beneath the Magothy formation, which locally lies at the base of the Upper Cretaceous series in the New England Islands.

The most continuous exposure of the Upper Cretaceous series in the area here considered is that seen in the cliffs at Gay Head (see plate **14**); but even there, owing to the complex of overturned folds and thrust faults, neither the number, the exact order, nor the thickness of the beds can be exactly determined except for a small part of the section. The following section may be seen in the cliffs at Gay Head, in front of the lighthouse:

Section of Upper Cretaceous Beds Exposed at Gay Head

Quartz-bearing kaolinite at top, bleached white, alternating with a bed of white clay about four feet thick and merging into cross-bedded quartz gravel below. The cast of a pelecypod (cf. *Pholadomya* sp.) was found in a "quadrangular fold" in the kaolinite at the top of the series. Probably marine in its upper part.

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[1] Jour. Geology, **23**, pp. 608–618, 1915.

White clay, in places stained deep red. Carbonized leaves of fossil plants found here and there above the underlying bed of lignite. Same flora found in nodules at places where the lignite has been forced over the clay, which has there become brownish from infiltrated iron stains. Nonmarine.

Lignitic clay and lignite at bottom; exposed only in close anticlinal folds. Contains broken trunks of trees and fragments of coniferous wood (*Brachyphyllum*, *Prepinus viticetensis* Jeffrey),[1] and amber. Nonmarine.

The total thickness of the beds in this section probably does not exceed 150 feet. On the south side of the cliffs there is a long exposure of overturned beds of clay, mottled white and red, having an apparent thickness of several hundred feet, but the beds are undoubtedly repeated by folding. The narrow, squeezed masses of white Cretaceous clay in closely folded beds at Ball's Point, on Block Island, as well as most sections of the clay that are not associated with lignite or that contain no fossil leaves afford little clue to their stratigraphic position.

Marine fossils found near Indian Hill by Shaler in somewhat drifted blocks of sandstone, an indurated part of one of the Cretaceous beds, show that the marine division of the Upper Cretaceous system probably occurs on Marthas Vineyard. Shaler regarded these fossils as not later than middle Cretaceous. They probably belong at a horizon above the lignitic beds at Gay Head. Several members of the United States Geological Survey have collected Cretaceous invertebrate fossils in drifted argillaceous boulders on Marthas Vineyard. According to L. W. Stephenson, most of the species are nearly identical with those found in the poorly preserved material collected by Shaler. The wide distribution of these boulders over the island indicates that marine upper Cretaceous beds once covered this district, and extended inland northward and northwestward.

Stephenson regards the deposit on Marthas Vineyard as of Matawan age and states that if *Exogyra ponderosa* has been correctly identified among the fossils from the island, the fauna certainly falls within the zone of *Exogyra ponderosa* in the Matawan.[2]

Tertiary System

EOCENE AND OLIGOCENE SERIES

The Tertiary system is divided into the Eocene, Oligocene, Miocene, and Pliocene series, which are here named in ascending order. The Eocene and the Oligocene series are not represented by any known deposits that stand above sea level in southeastern Massachusetts and Rhode Island. Fragments of an Eocene fossiliferous limestone have been recognized by W. O. Crosby in the glacial drift near the top of the bluff at Highland Light, on Cape Cod, and fragments of a reddish friable sandstone containing Eocene fossils have been found in glacial deposits on Chappaquiddick Island. These fragments may have been dragged by glaciers from the bottom of the Bay of Maine, where, possibly, Eocene beds still exist, but they afford scant evidence that the Eocene sea encroached upon the lowland of southeastern Massachusetts inside the present shore line.

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[1] Jeffrey, E. C., Annals of botany, **20**, No. 80, pp. 383–394, pl. 28, 1906. Also Proc. Boston Soc. Nat. Hist., **34**, pp. 333–338, pl. 33, 1910.

[2] Report on collections of Upper Cretaceous invertebrate fossils from Marthas Vineyard, Mass.

The Eocene rock found by Crosby[1] in the glacial gravel at Highland Light was described by him as occurring about half a mile south of the lighthouse up to a height of 125 feet and for 20 to 30 rods along the face of the cliff. It is a firm, massive white, calcareous sandstone, which effervesces freely with acid, and yet to the eye is composed principally of rounded grains of transparent quartz. It contains also minute grains of glauconite, vestiges of lignite, and grains of iron oxide. The fossils, which are in the form of molds or internal casts, are only fragments. Crosby's list and notes are given below:

Eocene Fossils Found in Fragments of Limestone in Drift at Highland Light, Cape Cod

Venericardia planicosta Lamarck. Found also in lower Eocene of Virginia
V. parva Lea?
V. alticosta Conrad?
Casts of fragments of two other species of *Venericardia*
Ostrea divaricata Lea. Possibly *O. sellaeformis* Conrad. Found also in the lower Eocene of Alabama
O. virginianae?
Ostrea sp. A large thick shell
Plicatula filamentosa Conrad, or a form very near this species
Camptonectes clavatus Conrad. Found also in middle Eocene in South Carolina
Axinaea staminea Conrad? Fragmentary shells, difficult to determine
Cardium sp.
Yoldia or *Nuculana* sp.
Corbula sp.
Turritella sp.
Natica sp.
Cidaris sp.
Galaxea sp.

Crosby inferred that these fossil-bearing boulders were derived from an Eocene bed somewhere north of Cape Cod, in the region of the floor of Massachusetts Bay, but more recent investigations indicate that the boulders brought to that part of the Cape by the ice were moved west of south. These Eocene boulders were evidently found in drift that had been shifted and worn by the action of water after they had been released from the ice. If the clay of the so-called "clay pound" at Highland Light is of the same age as the Gardiners clay, found farther southwest, the beds of gravel containing these boulders are of Jameco age; they were laid down in the third stage of the glacial epoch.

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[1] Proc. Boston Soc. Nat. Hist., **20**, pp. 136–140, 1879.

Of the Oligocene series no trace has been found in the district. The Oligocene epoch appears to have been a time of erosion, in which at least the coastal border of the lowland was reduced to its present relief, but as the overlying marine deposits are not the earliest of that epoch, the erosion may have begun before Oligocene time and continued after its end.

MIOCENE SERIES

The Miocene series is represented in this region by remnants of deposits of greensand, which are seen at Gay Head, on the west coast of Marthas Vineyard; on Nonamesset Island; and at Marshfield and Duxbury, Mass., on the mainland, about six miles north of Plymouth (see Pl. 4). There was formerly a small deposit of this greensand, carrying much clay, in the Nashaquitsa cliffs, but it was carried away several years ago by the retreat of the cliffs.

EARLY INVESTIGATIONS

Locally, at Gay Head, the greensand appears to be underlain by a deep blue clay containing the same assemblage of fossils as the greensand bed. The greensand, with its fossil crabs, shark teeth, and casts of mollusks, found during the first geological survey of the state at Gay Head, on the west end of Marthas Vineyard, and in Marshfield on the mainland, ~~were~~ was identified as of Miocene age by Lyell at the time of his visit to Gay Head in April, 1842. Lyell also assigned to the Miocene series the plant-bearing beds on Marthas Vineyard, but he greatly overestimated the thickness of the beds. Shaler adopted his estimates in his first report on the geology of Marthas Vineyard but modified it later. At Marshfield the Miocene beds are exposed in wells and are apparently about 30 feet thick and undisturbed. At Gay Head the entire Miocene section, which varies greatly in constitution as well as in thickness as seen in the cliffs, is probably nowhere more than 10 feet thick.

In 1895 Dall attempted to correlate the Miocene of this region with the Miocene formations in the Atlantic coastal plain south of New York. After examining the fossils collected at Gay Head and Marshfield and visiting the Gay Head section he referred the greensand and the associated osseous conglomerate of President Hitchcock's report to the Chesapeake or "newer Miocene," which along the Atlantic coast contains a colder water fauna than that of the "older Miocene."

In 1889[1] in a geologic section illustrating Shaler's paper on the "Tertiary and Cretaceous deposits of Massachusetts," I divided the Miocene at Gay Head into two parts, described in descending order as follows:

5. Greensand beds and boulders of No. 4
4. Osseous or quartz pebble conglomerate

The osseous conglomerate was represented as resting on eroded Cretaceous beds, the age of which had been determined by means of White's work on the fossil flora found at Gay Head. The beds of granitic gravel, sand, and boulders that overlie the greensand were referred to an interglacial and preglacial stage.

In 1897, in a paper on the unconformities of this part of the coastal plain,[2] I stated that the Miocene at Gay Head is made up of two well-defined lithological divisions, and probably a third, which might be Pliocene. Dall later gave reasons for so regarding it. The Miocene divisions were identified as the osseous conglomerate of Hitchcock, which was regarded as a basal member, and the supposed later greensand, or foraminiferal bed. Rolled fragments of the osseous conglomerate were described as occurring in the basal part of the greensand bed, which is found east of those parts of the cliff in which unbroken osseous conglomerate is seen in place. The determination of the sequence of the deposits was based on the occurrence of small boulders of the osseous conglomerate in the position indicated. Up to this time no doubt had been expressed that the osseous conglomerate bed is a member of the Miocene series, as Lyell thought in 1842 and Dall in 1895.

In 1900 I published a notice of the finding of the astragalus of a fossil horse in the osseous conglomerate at Gay Head in May, 1889.[3] H. F. Osborn, to whom the bone was submitted for examination in 1900, expressed the opinion that the bone was that of a Pleistocene type of horse, and the question arose whether it was found in the osseous conglomerate or in an overlying bed of glacial gravel. The statement was made that "The bone was broken in extracting it from the bed, and there can be no doubt about its occurrence as a constituent of the osseous conglomerate."[4] On the same visit during which this bone was found, another imperfectly preserved mammalian bone was collected from the osseous conglomerate in the same place, just east of the "Devil's Den," in the folded beds figured by Edward Hitchcock in his report of 1841, but this bone was not identified until 1916, when Dr. Glover M. Allen found it among the collections of the Museum of Comparative Zoölogy, and recognized it as a fragment of the skeleton of a Pliocene camel. It, therefore, appears that the osseous conglomerate is made up of a mixture of the bones of marine and land animals that ranged in age from Miocene to earliest Pleistocene and can hardly be regarded as a pre-Pleistocene deposit. An examination of the section in 1916 threw no further light on the question. The boulders of conglomerate in the greensand were either derived from some underlying formation in the Cretaceous system or were thrust into the greensand from above, as boulders are rolled along and sink in soft mud.

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[1] Bull. Geol. Soc. America, **3**, pp. 443–452, pl. 9, 1889.

[2] See bibliography.

[3] Woodworth, J. B., Glacial origin of older Pleistocene in Gay Head cliffs, with note on fossil horse of that section, Bull. Geol. Soc. America, **11**, pp. 459–460, pl. 42, fig. 2, 1900.

[4] *Op. cit.*, p. 459.

The paleontologic evidence, though scant, is here accepted as sufficient to call for such a revision of the classification of the Miocene and early Pleistocene deposits at Gay Head as will remove the conglomerate and its abundant Miocene fossils to a position at the base of the Pleistocene.

CHARACTER OF THE DEPOSITS

The Miocene deposits of this region consist of beds of greensand, most of which are brownish red, weathered, somewhat compacted masses of small grains or nodules, which near the base of the bed, or deeper within the section, become greenish to bright green, the color of typical greensand. The larger grains are between 0.5 mm. and 1.5 mm. in diameter, and many of them show the outlines of the well-known foraminifers of greensand deposits.[1] The presence of these beds in the Miocene series in this part of the Atlantic coastal plain is somewhat anomalous, and W. B. Clark and F. J. H. Merrill have raised the question whether the beds may not have been redeposited from a marine Cretaceous section that was invaded and partly reworked by the advance of the Miocene sea. The Miocene age of the greensand bed is indicated by the fossil mollusks and vertebrates it contains. The greensand is relatively pure, but at Gay Head a few rounded, highly polished quartz pebbles are found in the middle of the bed, and near its base there are numerous coarse grains of quartz. The bed of greensand exposed on the southwest side of Nonamesset Island contains a large percentage of coarse rounded quartz grains, 3 to 4 mm. in diameter, literally a fine gravel.

GASTROLITHS IN THE GREENSAND AT GAY HEAD

The greensand bed at Gay Head contains scattered, smooth, shining quartz pebbles, the largest 1½ inches long. The high polish of these pebbles and their association with the fossil remains of a supposed seal and a walrus suggest that they are the stomach stones or gastroliths of seals. Sir John Murray[1] states that both seals and penguins carry to sea in their stomachs large numbers of stones and pebbles, which sealers call "ballast." He remarks that "these animals may, therefore, to some extent distribute rock fragments to great distances from the land; should any of them be killed or die at sea their soft parts might be entirely removed in solution, and even their bony structures might be entirely removed, while the stones and pebbles contained in their stomachs would remain as a part of the deposit."

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[1] Cushman, Joseph Augustine, Some Pliocene and Miocene foraminifera of the coastal plain of the United States, U. S. Geol. Survey Bull. 676, p. 100, 1918.

Moseley[2] too states that "stones are found in all seal stomachs, apparently just as in those of penguins."

GASTROLITHS AT DUXBURY AND MARSHFIELD

The Miocene deposits of the mainland in Duxbury and Marshfield were first described by Hitchcock in 1833.[3]

> Here were found a very perfect shark's tooth, the case of a small species of *Venus*, and the same species of *Turbo* that occurs at Gay Head. In another specimen of *Venus*, in the cavity occupied by the hinge, is a small quantity of greensand, exactly like that at Gay Head, which proves satisfactorily the identity of the marsh mud and the greensand; and that the greensand of Gay Head is identical with that in England a comparison of specimens shows.

Hitchcock again visited the greensand area in Marshfield and Duxbury in 1837, when certain wells were open, and found that greensand had been thrown out from at least three wells.[4]

A chemical analysis of the greensand from Marshfield by Dr. S. L. Dana was published by President Hitchcock in the same report.[5]

In the Final Report on the Geology of Massachusetts, published in 1841 (page 91–92), Hitchcock reprinted, without additional comment, the statements concerning the greensand in Duxbury and Marshfield.

In 1850, Dr. Jackson,[6] of Boston, stated, in remarks on the Tertiary deposits at Marshfield, that a shark's tooth, a cetacean vertebra, lignite, and the cast of a *Tellina* had been found in clay marl over a deposit of greensand at a depth of 30 feet from the surface.

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[1] Report on deep-sea deposits. The Voyage of the Challenger, pp. 323–324. Zoölogy of the Challenger Expedition, pt. 8, pp. 126–127; also Turner, Report on Seals, Zoöl. Challenger Exp., pt. 68, p. 136.

[2] Notes by a naturalist made during the voyage of the Challenger, revised edition, New York and London, 1892, p. 178. Moseley notes that penguins are eaten by seals (p. 164); hence seals may not voluntarily take up pebbles from the shore or the bottom.

[3] Hitchcock, Edward, Report on the geology, mineralogy, botany and zoölogy of Massachusetts, pp. 199–201, Amherst, 1833.

[4] Hitchcock, Edward, Report on a reëxamination of the economical geology of Massachusetts, p. 76, Boston, 1838.

[5] Hitchcock, Edward, *op. cit.*, p. 77.

[6] Jackson, Charles T., Proc. Boston Soc. Nat. Hist., **3**, pp. 323–324, 329, 1851; also Proc. Am. Assoc. Adv. Sci., **4**, 1851, p. 251.

In 1890 Shaler[1] published a brief report on a geologic examination of the greensand deposit at Marshfield, made with the help of his assistant, C. P. Sinnott. Shaler remarks that the area occupied by the greensand, as shown in excavations, covers more than a square mile. The material consists of layers of greensand substantially like those at Gay Head. The beds appear to be horizontal. The few molluscan remains found were regarded as possibly of Cretaceous age.

The greensand collected by Mr. Sinnott contained a few marine fossils — the casts of two mollusks (see Pl. 5), and fragments of crabs, one like that common at Gay Head and the other an undescribed form with a very large telson.

Fossils in Greensand at Marshfield, Mass.

- Mollusks:
  - *Panopaea* sp. cf. *P. goldfussi* Wagner. Internal cast of both valves.
  - *Venus* sp. cf. *V. campechiensis* var. *mortoni* (Conrad). Internal cast of right valve.
- Crustacea:
  - *Cancer proavitus* Packard.[2]

The fossil shell that Jackson called *Tellina* is probably the *Macoma lyelli* of Dall, which is common in the greensand bed at Gay Head. The fossils found at Marshfield and the bed containing them resemble so closely the fossils and the bed at Gay Head that the two beds probably belong at the same stratigraphic horizon.

The deposition of the greensand at Marshfield directly on the granitic surface, without any remnants of the intervening Cretaceous beds found on Marthas Vineyard, shows that there is a great gap here between the Upper Cretaceous and the Miocene, a gap including all of the Eocene and Oligocene epochs.

ORIGIN OF THE GREENSAND

Late in Miocene time the sea invaded the lowland of Massachusetts and Rhode Island, as shown by the position of the beds of greensand in Marshfield and Duxbury, which rest on the granite that then formed the border of the continent. The beds of the same age on Marthas Vineyard, at Gay Head, have undergone so much deformation and dislocation that their present elevation above the sea, in the crest of folds, does not indicate that they were laid down above sea level. The depth below sea level and the distance from shore at which the beds of greensand and their fossil crabs, fish, and marine mammals were laid down are not certainly known. The deposits of greensand that are now being formed on the sea floor lie so far out at sea that relatively little mud and sand reaches them from the shore. Pure greensand is laid down in water having a depth as great as 900 fathoms, but it may accumulate in shallower water at places where mud and sand are excluded from it by the nature of the shore or by the absence of offshore currents to carry out débris from the land. The presence of grains of quartz in the Miocene beds at Marshfield and Gay Head show that those beds were laid down in relatively shallow water. The bed of greensand at Nonamesset, which lies nearer the theoretical shore line of the Miocene sea, contains much more quartz and coarser grains of it than the bed at Gay Head. Conditions for the deposition of greensand containing terrigenous material would probably be provided by the submergence of the lowland of eastern Massachusetts and Rhode Island to a depth that would carry the shore line in the longitude of Worcester up to the present 500-foot level. Such a shore line would extend nearly northward, passing through the eastern parts of the Kent, Burrillville, Blackstone, Marlboro, and Groton quadrangles. The remnants of the beds of greensand at Marshfield and Gay Head now lie about 45 miles seaward from the 500-foot contour line, and the depth of water over them, under the conditions here assumed, would have been somewhat more than 450 feet. Most of the present coast of eastern Massachusetts would then have been submerged.

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[1] Shaler, N. S., Tertiary and Cretaceous deposits of eastern Massachusetts, Bull. Geol. Soc. America, **1**, p. 447, 1890. Also Report on the Atlantic Coast Division, Eleventh Ann. Rept. U. S. Geol. Survey, pt. 1, p. 63, 1891.

[2] Packard, A. S., A new fossil crab from the Miocene greensand bed of Gay Head, Marthas Vineyard, Proc. Am. Acad. Arts and Sci., **36**, pp. 3–9, pls. 122, 1900. Cushman, J. A., Fossil crabs of the Gay Head Miocene, Am. Naturalist, **3**, pp. 381–390, pls. 1, 2, 1905.

The casts of mollusks and crustaceans and the bones of cetaceans found at Gay Head and Marshfield suggest the depth of the water there, but their probable mode of burial should be considered before conclusions based on them are formed. The bones of the cetaceans are strewn through the deposits in a way to indicate that they were laid down at about the same time as the foraminifers that make up most of the greensand. The remains of crabs found in the greensand were probably also entombed with the growth of the deposits. Shallow water is preferred by species closely allied to those found in these beds of greensand. Of the mollusks, particularly the clam-like forms, one of which (*Macoma lyelli*) is found with both valves intact, in the attitude of life, in the greensand at Gay Head, it may be said that they might have lived beneath the surface of the bed of greensand after the water above it had become shallower than that in which it was deposited. The late Miocene sea, therefore, may not have stood above the upland about Worcester, for if it had reached that height the land to the west would have stood so high that its position could not be harmonized with the indications of shallow water over the remnants of the Miocene offshore deposits.

The greensand beds give little indication of the conditions near and along the shore, for they contain no detrital material that can be traced to the Paleozoic rocks of the inland. The pebbles and grains of quartz in the greensand may have been derived from the remnants of Cretaceous beds over which the Miocene sea transgressed after an epoch of Oligocene land. No definite trace of the Miocene shore has yet been recognized and, as the Miocene beds contain no waste derived from the ancient rocks, the marine invasion in Miocene time must have been short and could not have left strongly marked sea cliffs in the crystalline rocks of the upland.

CHEMICAL ANALYSES OF THE GREENSAND

The greensand in Marshfield and on Gay Head has never been used in agriculture, so its chemical analyses are incomplete. Three analyses that have been published are reprinted below, along with analyses of other greensands.

Chemical Analyses of Greensand

Constituents	1	2	3	4	5	6
SiO_2	. .	. .	56.70	49.23	51.25	50.85
Al_2O_3	. .	. .	13.32	7.11	7.25	8.92
Fe_2O_3	. .	. .	20.10	20.89	20.72	21.40
FeO	. .	. .	. .	3.00	. .	1.66
MnO	. .	. .	tr.	tr.	. .	. .
CaO	0.65	1.09	1.62	tr.	. .	1.26
MgO	. .	. .	1.18	3.44	5.98	3.13
Na_2O	0.33	0.38	. .	0.11	1.92	0.25
K_2O	4.16	3.87	. .	8.51	6.21	4.21
H_2O	. .	. .	. .	1.83	6.49	5.55
H_2O+	. .	. .	. .	4.88	. .	. .
P_2O_5	0.22	0.48	. .	. .	. .	. .
CO_2	0.14	0.16	. .	. .	. .	. .

Sources of the Materials Analyzed

1. Material resembling greensand from north end of Gay Head section. Analysis made in the laboratory of the U. S. Geological Survey and reported to Professor N. S. Shaler by F. W. Clarke, Seventh Ann. Rept. U. S. Geol. Survey p. 360, 1888.
2. Same as 1. Both 1 and 2 were partial analyses.

3. Glauconite from Gay Head; analysis by Dana. Dana, J. D., and Brush, J. G., Descriptive mineralogy, 9th ed., New York, p. 462, 1889.

4. Glauconite from Big Goose Canyon, 15 miles southeast of Sheridan, Wyo. Analysis by George Steiger (sp. gr. 2. 73). From Analysis of rocks and minerals, U. S. Geol. Survey Bull. 591, p. 340, 1915.

5. Glauconite from an igneous rock at Mount Baldo; analysis by Delesse, 1848. Dana, J. D., and Brush, J. G., Descriptive Mineralogy, 9th ed., New York, p. 462, 1889.

6. Glauconite from Station 164B (410 fathoms), No. 85. Report of Challenger Expedition on deep-sea deposits, p. 387.

For references to important papers on glauconite and additional analyses of materials from foreign localities, see Clarke, F. W., The data of geochemistry, U. S. Geol. Survey Bull. 330, pp. 439–442, 1908; and Bull. No. 491, pp. 492–494, 1911. On the Cretaceous greensand of New Jersey and its origin, see Clark, W. B., A preliminary report on the Cretaceous and Tertiary formations of New Jersey, Ann. Rept. State Geologist for 1892, pp. 218–239, and Plates 4–6, reproduced from Challenger Expedition report. Analyses of New Jersey greensands at p. 230. Clark (p. 220) cites Pourtales as reporting greensand at depths from 50 to 100 fathoms on the present sea floor off the coasts of Georgia and South Carolina.

See also Ashley, G. H., Notes on the greensand deposits of the eastern United States, U. S. Geol. Survey Bull. 660, pp. 27–49, 1918; Goldman, M. I., The petrography and genesis of the sediments of the Upper Cretaceous of Maryland, Maryland Geol. Survey, Upper Cretaceous, pp. 111–182, 1916; Collet, L. W., Les depôts marins, pp. 132–194, 303–306, Paris, 1908; and Thoulet, M. J., Étude bathylithologique des côtes du golfe de Lion, Inst. océanographique Annales, **4**, No. 6, pp. 62 et seq., Paris, 1912.

FOSSILS FROM THE GREENSAND AT GAY HEAD AND NASHAQUITSA

Of the fossils collected from the greensand beds in the Gay Head cliffs in 1889 by Dr. A. F. Foerste and J. B. Woodworth, Dall identified the following species:

Yoldia limatula Say
Nucula shaleri Dall
Arca (like *A. ponderosa* Say)
Angulus sp.
Macoma lyelli Dall
Lucina sp.
Venus mortoni Conrad
Macrocallista? sp.
Venus (*Gemma*) *purpurea* Lea
Mya, probably *M. arenaria* L.
Panope goldfussi Wagner
Cardium virginianum? Conrad
Chrysodomus (cf. *C. liratus* Martyn)
Chrysodomus, probably *C. stonei* Pilsbry
Pecten (cf. *P. irradians* Lam.)
Solen solen (fragment)

Cardium virginianum Conrad, listed with the species found in the greensand bed, is found on the cliff in the talus just below the outcrop of the osseous conglomerate. A specimen was found there by me in 1889, and Professor Charles Killam of Harvard University picked up a specimen of the same species at about the same place in my presence in 1917. The casts are composed of a white kaolinite containing grains of quartz, and the bed is apparently identical with that beneath the Aquinnah[1] or the osseous conglomerate of Hitchcock, which is usually regarded as of Upper Cretaceous age. In the broken interior of the specimen collected in 1917 there is a tooth, about 2 mm. long, of a small fish having the habit of minute forms referred to *Lamna cuspidata* Agassiz, which ranges in New Jersey from the Cretaceous ? through the Eocene into the Miocene. No specimens having this matrix of white kaolinite have been seen in place at Gay Head. If a specimen of *Cardium virginianum* should be found in place in the kaolinite bed below the osseous conglomerate, it would indicate that the Chesapeake Miocene included beds of white clay and kaolinite older than the osseous conglomerate and probably also older than the bed of greensand, but younger than the beds carrying identifiable remains of Cretaceous plants.

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[1] Aquinnah, the Indian name for Gay Head, is used in this report for the osseous conglomerate of Hitchcock.

A fragment of the inner cast of the body whorl of a species of *Nassa* found in the greensand bed at Gay Head in October, 1917, by Mr. L. G. Darrow, of Cambridge, Mass., was submitted to Dr. Dall, who remarked its essential agreement in sculpture with the Miocene *Nassa trivitattoides* of Whitfield, from New Jersey, a species occurring also in the Miocene of Maryland, and ranging there from the Calvert formation upward into the Choptank. The species is restricted to the Miocene.

The species above named were obtained from the greensand beds in cliffs at Gay Head between Stations 13 and 35 of the map of Gay Head published in 1897 in volume 8 of the Bulletin of the Geological Society of America as Plate 16.

The fossils collected in 1889, mainly by me, from Nashaquitsa cliffs on what was known as the Ephraim Mayhew farm, were also reported on by Dall in 1916 as containing the following species:

Macoma lyelli Dall
Nucula shaleri Dall
Yoldia (cf. *Ysapotilla* Gould)
Panopea goldfussi Wagner
Pecten magellanicus Gmelin
Acmaea sp.
Modiolaria laevigata Gray
Venus mercenaria L. (young)
Solen sp.
Euspira? sp.
Barnacle valve

To these fossils should be added the single mesial dental or plate tooth of a species of *Miliobates* found in the greensand bed at Nashaquitsa in September, 1889, but unfortunately lost in transportation.

The fossil shark teeth and the fish vertebrae found in the greensand, particularly those found in the Aquinnah osseous conglomerate, have not been identified. Many teeth pertaining to species of *Carcharodon*, *Otodus*, *Galeocerdo*, *Hemipristis*, and possibly other genera have been collected.[1]

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[1] For illustrations of similar fossil fish teeth see Fowler, H. W., A description of the fossil fish remains of the Cretaceous, Eocene, and Miocene formations of New Jersey, Bull. Geol. Survey of New Jersey, 4, p. 192.

The tooth of a mid-Tertiary rhinoceros and the rib of a walrus were collected from the Miocene greensand bed at Gay Head by Mr. Daniel Vincent of Chilmark, Mass. These and other vertebrate fossils from the greensand and from the Aquinnah conglomerate (Hitchcock's osseous conglomerate) have been examined and described by Dr. G. M. Allen.

The Aquinnah conglomerate and the greensand bed should be thoroughly explored for other fossils, particularly the Aquinnah conglomerate, the only known occurrence of which in place is in the face of Gay Head cliffs.

A few fossils were found at Gay Head under circumstances that make it doubtful whether they originally came from the horizon of the greensand beds. Many fossils have been found in the Aquinnah conglomerate, which was once referred to the Miocene, but which now seems to be made up of débris derived from beds laid down at the beginning of the Pleistocene epoch, before the glaciers covered this district.

Edward Hitchcock[1] described and figured a tooth, which he referred to a crocodile, found at Gay Head in the "ferruginous sand," probably the oxidized greensand. This tooth is described as silicified, a fact that led him to doubt its geologic horizon. The specimen cannot now be found.

Lyell[2] visited Gay Head in April, 1842, and collected some characteristic fossils, in addition to which he found in the hands of a fisherman a part of the skull of a walrus differing, as he thought, from the existing species (*Trichecus rosmarus* Linn.) in having one more tooth on each side of the upper jaw. The specimen is said to have been found in the osseous Aquinnah conglomerate.

Lyell also collected from the osseous conglomerate several rolled cetacean bones, one of which he illustrates under the generic name *Hyperoödon* and another under *Delphinus*. Large numbers of these bones have been taken from the bed or picked up on the slopes below it and along the adjacent beach, where they become blackened on contact with sea water. Some of these have been described and illustrated by Allen,[3] who refers certain vertebrae to the finback whale

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[1] Hitchcock, Edward, Report on the geology [etc.] of Massachusetts, p. 103, Amherst, 1833. Plates illustrating the geology and scenery of Massachusetts, pl. xl, fig. 16, 1833. Catalogue of specimens, Appendix p. 655. Specimen No. 103. See also Hitchcock's Final report on the geology of Massachusetts, pp. 330–341, pl. 19, fig. 13, 1841. Catalogue of State Collection, p. 803, specimen No. 103. Also in the collection of rocks, minerals, and fossils in the State Cabinet of the Agricultural Museum at Amherst. Catalogue of December 1, 1858, p. xvii. Section IV, Miocene Tertiary, specimen No. 48. Sixth annual report of the secretary of the State Board of Agriculture for 1858. Appendix.

[2] Lyell, Charles, Travels in North America, **1**, p. 258, pl. v. London, 1845. Also American ed., p. 204, pl. v, New York, 1845.

[3] Allen, G. M., The whalebone whales of New England, Memoirs Boston Soc. Nat. Hist., **8**, No. 2, pp. 257, pls., 1916. Description based on collections of the Museum of Comparative Zoölogy, Nos. 3742, 9742, 8743, 8744; and the Boston Society of Natural History, No. 9698.

(*Balaenoptera? sursiplana*). He states that at least four genera of cetacea are represented by the collections, among them the tooth of a squalodon (*Basilosaurus atlanticus*), which has also been found at Shiloh, New Jersey.

Crustacea are represented in the greensand by a barnacle (*Balanus concavus* Brown) and two genera of crabs (*Archaeoplax signifera* Stimpson, and *Cancer proavitus* Packard).[1]

FOSSILS FROM THE GREENSAND AT MARSHFIELD AND DUXBURY

The Miocene greensand and the overlying clay marl at Marshfield and Duxbury have afforded only a few fossils, some of which are not in existing collections. The list of fossils below summarizes the notes given elsewhere in this report.

Fossils from the Miocene Greensand and the Overlying Clay Marl at Duxbury and Marshfield, Mass.

- Foraminifera:
  - Casts of several unidentified species
- Gastropods:
  - *Fulgur?* sp. (Turbe of Edward Hitchcock)
- Pelecypods:
  - *Venus?* sp.
  - *Venus* sp. cf. *campechiensis* var. *mortoni* Conrad
  - *Panope* sp. cf. *P. goldfussi* Wagner
- Crustacea:
  - *Cancer proavitus* Packard
  - Large claw of a crab (?), poorly preserved
- Fishes:
  - *Oxyrhina desori* Agassiz
- Mammals:
  - Cetacean bone (unidentified)

MIOCENE FOSSILS FROM OTHER DEPOSITS

At Nashaquitsa cliffs, on the south side of Marthas Vineyard, a considerable number of Miocene fossils, most of them waterworn, have been found in basal Pleistocene gravel and sand. In 1889, in an hour's search, I collected 70 fish teeth, mainly those of sharks, from a bed of coarse sand that is believed to lie below the Jameco gravel, probably the bed here called *Weyquosque Sand.*

[1] Stimpson, William, On the fossil crab of Gay Head, Boston Jour. Nat. Hist., **7**, pp. 583–589, 1863. Packard, A. S., A new fossil crab from the Miocene greensand bed of Gay Head, Marthas Vineyard, with remarks on the phylogeny of the genus Cancer, Proc. Am. Acad. Arts and Sci., **26**, pp. 1–9, 1900. Cushman, J. A., Fossil crabs of the Gay Head Miocene, Am. Nat., **39**, pp. 381–390, pl. 2, 1905, includes a restoration of *Archaeoplax signifera.* Collections in the Museum of Comparative Zoölogy and the Boston Society of Natural History.

PHOSPHATIC NODULES IN THE GREENSAND

In addition to the nodules containing fossil crabs in the greensand bed at Gay Head, there are numerous dark nodules having irregular surfaces, which Lyell spoke of as coprolites. These nodules range in diameter from one to two inches. An analysis made for Lyell showed that they contain no less than 50 per cent of phosphate of lime, together with fluoride of calcium, chloride of sodium, and other constituents.[1] Shaler, for whom a partial analysis of similar

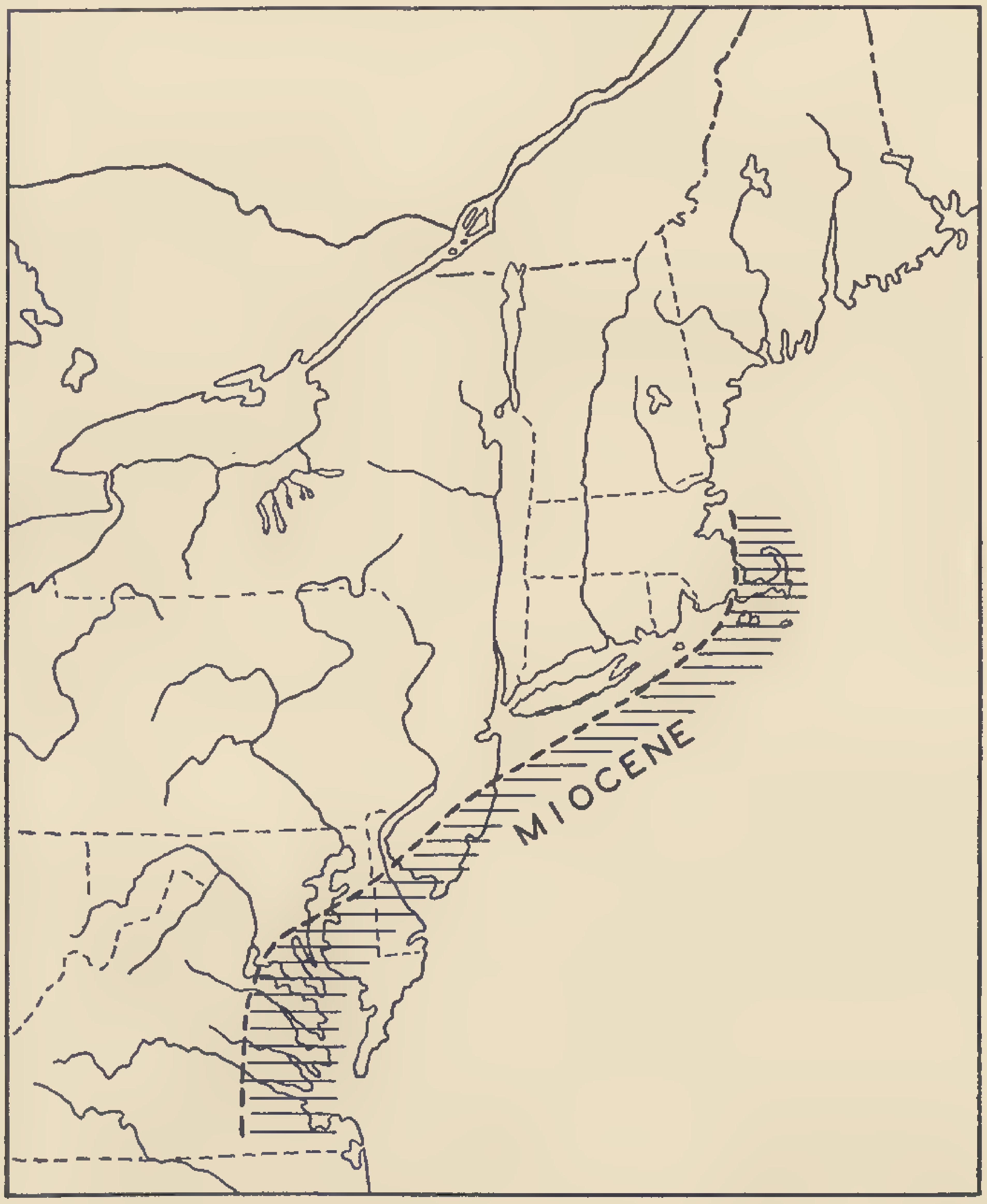

Fig. 2.— Map showing the probable Miocene boundary from Massachusetts southward to Chesapeake Bay.

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[1] Lyell, Charles, Travels in North America, **1**, p. 257, London, 1845. American edition, **1**, p. 204, New York, 1845; Shaler, N. S., Report on the geology of Marthas Vineyard, Seventh Ann. Rept. U. S. Geol. Survey, p. 360, 888.

material from Gay Head was made in the laboratory of the United States Geological Survey, states that it is made up as follows:

Phosphoric acid (P_2O_5)	23.00
Carbonic acid (CO_2)	2.60
Lime (CaO)	25.73
Potash (K_2O) Soda (Na_2O)	0.15
Silica (SiO_2)	17.82

Many of the nodules enclose remains of crabs and casts of foraminifers and of the mollusk *Macoma lyelli.* This association accords with the statement of F. W. Clarke that "the organic remains which contribute to the formation of phosphorites vary widely as regards richness in phosphates. Bones are the richest; crustacean remains probably come next; mollusks and corals are the poorest."[1] The mode of segregation of the phosphate of lime in the nodules does not indicate that they are coprolitic, but the shape of some of them countenance this view.[2] Most of these concave-convex, lumpy nodules bear no resemblance to the fusiform, transversely constricted objects described as coprolites by their discoverer.[3] Moreover, the segregations of nodular crust about uncrushed and undigested carapaces and legs of the fossil crab *Archaeoplax signifera* in the greensand bed shows that the nodulation took place through chemical processes after the deposit of greensand had been formed.

Penrose[4] mentions the nodules at Gay Head as "amorphous nodular phosphates" and states that they have a waterworn appearance and have a hardness of about 3. He states that they give off decayed organic matter when two fragments are rubbed together. He further remarks that the nodules are too widely scattered in the bed and hence too expensive to mine for commercial use.

EASTWARD EXTENSION OF THE MIOCENE DEPOSITS

Only two patches of Miocene deposits are exposed along this coast, that at Gay Head and that on Nonamesset Island. In addition, however, there are covered beds in Marshfield and Duxbury. Beds of Miocene greensand probably once extended along the coast as a sheet, of which the present patches are remnants. Fossils found in glacial drift on Nantucket must have been derived from Miocene beds. In 1890 I found a Tertiary fossil near Shimmo Point and Miocene fossils near Polpis Harbor, both on Nantucket. I also found a nodule of greensand in the drift 1½ miles west of the town of Nantucket, and in 1915 I found a waterworn tooth of a shark (*Megalodon*) in a bed of Sankaty sand at Squam Head, near the east end of Nantucket. The Miocene deposits of Nantucket, like most of those of Marthas Vineyard, Block Island, and Long Island, were probably wholly removed by the action of the sea and of the ice at the beginning of Pleistocene time.

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[1] Clark, F. W., The data of geochemistry, 2d ed., U. S. Geol. Survey Bull. 491, p. 500, 1911.

[2] See Buckland, Trans. Geol. Soc. London, **3**, new ser., pt. 1, p. 234 et seq., with three plates, 1892; also same author in Geology and Mineralogy, 4th ed., **1**, pp. 164–176, London, 1869, and **2**, Atlas, pl. 17, 1870.

[3] See Bertrand, E. E., Les coprolithes de Bernissart, Memoires Musée Royal d'Histoire Naturelle de Belgique, **1**, pp. 1–154, pls. 1–15, Bruxelles, 1903.

[4] Penrose, R. A. E., Nature and origin of deposits of phosphate of lime, U. S. Geol. Survey Bull. 46, p. 78, 1888.

The Miocene marine deposit of southeastern Massachusetts affords the northernmost trace of the Atlantic Ocean on the east coast of North America in mid-Tertiary time. (Fig. 2, p. 28).

PLIOCENE SERIES

A thin bed of marine sand containing a Pliocene marine fauna was found by Gratacap near Southampton, Long Island, and fossiliferous sands of Pliocene age have been recognized by Dall at Gay Head, on Marthas Vineyard.

Dall,[1] who examined and identified the marine fossils in a large collection made at Gay Head, states that, "On the whole, these specimens indicate a more recent fauna than the Miocene on Marthas Vineyard and may perhaps be regarded as representing the Pliocene." These deposits of marine fossiliferous sand have apparently nothing in common with the so-called "Lafayette formation" of the southern coastal plain, though they occupy about the same stratigraphic position. The results of Dall's investigations at Gay Head would seem to favor their reference to an early rather than to a late Pliocene age, and they are, therefore, probably somewhat older than the "Lafayette formation." [2] No apparently equivalent beds of marine sand of Pliocene age have been recognized on the coastal plain north of Virginia.

Shell-bearing beds of sand have been found on Long Island, Gardiner's Island, Fisher's Island, at Gay Head, on Marthas Vineyard, and particularly at Sankaty Head, on Nantucket. Most of the fossil shells are those of species now living either in adjacent marine waters or along the coast south of New York. In the upper part of the section at Sankaty Head forms have been found which, though not now known on the Atlantic coast, are living in the seas of Alaska. Prior to the discrimination of the several divisions of the Pleistocene deposits in the New England Islands, all these fossiliferous beds were usually referred to a post-Pliocene date. For a time, indeed, Dana regarded the deposit at Sankaty Head as postglacial. Recent work has shown that certain deposits of sand contain extinct species as old as Pliocene. One such deposit lies near Southampton, on Long Island, and one was found in the cliffs at Gay Head, on Marthas Vineyard. At both places Miocene mollusks were found and at both the deposits rested directly on Miocene beds, so this horizon of fossiliferous sands is probably older Pliocene. The formation contains *Macoma lyelli* Dall at Gay Head and *Arca limula* on Long Island. Gratacap[1] describes the discovery of *Arca* (*Scapharca*) *transversa* Say, and *Arca limula* Conrad, in a "light yellow sandy marl," at a depth of 8 to 10 feet below the surface on the side of a bare hill in a road 6 miles east of Southampton, Long Island. Neither of these species is mentioned in the Maryland report on the Miocene (1904). Dall[2] states that *Arca limula* is confined to the Miocene in South Carolina, North Carolina, Maryland, and New Jersey, to the Pliocene in South Carolina, Georgia and Florida, that it is now extinct, and that it was probably the ancestor of *Arca ponderosa*. Gratacap refers the deposit on Long Island to the Pliocene.

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[1] Dall, W. H., Notes on the Miocene and Pliocene of Gay Head, Marthas Vineyard, Mass., Am. Jour. Sci., **48**, p. 300, October, 1894.

[2] On the general nature and interpretation of the so-called Lafayette formation, see Shaw, E. W., U. S. Geol. Survey Professional Paper 108-H, pp. 128–132, 1918.

The shell-bearing beds on Nantucket, known as the Sankaty sand in part, were referred by Dall to a late Pliocene age. In this report the Sankaty sand is referred to the Pleistocene, as it was by Fuller. There is an unquestioned older Pliocene horizon on the islands, known only in a fragmentary way, but probably having a considerable extension as a bed of sand, with or without fossils, beyond the two localities at which fossils have been discovered. The bed at Southampton, though not the first discovered nor the most richly fossiliferous, is the only known deposit that presents the possibility of yielding greater results on further exploration.

The older Pliocene in the cliffs at Gay Head, here correlated with the Tertiary beds of sand found at Southampton, was discovered in a small pocket that had been faulted down into the Miocene greensand bed. The deposit of sand was almost entirely removed in 1889. According to Dall[3] the fauna comprised the following species:

Venericardia borealis Conrad
Astarte castanea Say
Spisula polynyma Stm.
Corbicula densata Conrad
Macoma lyelli Dall?
Nucula shaleri Dall. var.?
Purpura lapillus L.

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[1] Gratacap, L. R., Tertiary fossils on Long Island, The Nautilus, **28**, pp. 85–86, 1914.

[2] Contributions to the Tertiary Fauna of Florida, 1898.

[3] Dall, W. H., Notes on the Miocene and Pliocene of Gay Head, Am. Jour. Sci., **48**, pp. 296–301, 1894.

Of these shells Dall remarked that *Corbula densata* had been found in the Upper Miocene of Virginia, that it occurs in the Pliocene of South Carolina, and that the *Venericardia* is one of a recent type rather than the Miocene *V. granulata*. The shells in these beds of sand at Gay Head had not been dissolved out, as are those in the underlying beds, a fact which implies a more recent origin than the apparently conformable contact of the beds of Pliocene sand in these deeper water deposits would indicate. The shells are broken as if by pressure exerted during the dislocation and folding of the beds.

If the beds of Miocene greensand and their shallow-water molluscan remains indicate the maximum depth and encroachment of the sea upon the Massachusetts lowland during the Miocene epoch, the beds of Pliocene sand at Southampton may be interpreted as marking a much shallower sea, which presumably covered the site of the New England Islands.

The deposit at Gay Head was found under the lighthouse at an elevation of 80 feet above the beach, but this elevation has no certain relation to the elevation of the formation prior to its deformation. The remnant of the formation on Marthas Vineyard was little more than a foot thick. The deposit on Long Island is apparently not more than a few feet thick.

The Sankaty sand on Nantucket Island, certain beds of which are by Dall referred to the newer Pliocene, is described below as a Pleistocene interglacial marine deposit.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

EARLY INVESTIGATIONS

New England is mantled with deposits of till, gravel, sand, and clay, the superficial parts of which, at least, were laid down by an ice sheet that came down southward to a front that extended along the New England Islands from Nantucket westward across Lond Island. On Cape Cod and the islands south of it these glacial deposits have been subject to great disturbance, as well as to erosion during epochs at least as long as those in which they were laid down (see Pl. 6).

In the earliest surveys of the New England Islands and Cape Cod the older granitic gravel and sand were usually assigned to the Tertiary system, the deposits of which in this region are inextricably intermixed with the Pleistocene beds by folding, faulting, and commingling. Thus, in the reports of Hitchcock, Lyell, and Shaler, the older Pleistocene as now determined was not distinguished from the latest Tertiary, although the glacial origin of certain beds in the Pleistocene of Marthas Vineyard had been suggested by Shaler in 1888.[1]

McGee[2] first recognized the Pleistocene age of certain deposits that are older than the so-called terminal moraine on the Atlantic slope. After Chamberlin had made his masterful survey of the drift sheets of the Mississippi Valley, McGee established the existence on the Atlantic slope of a group of Pleistocene deposits which he called the Columbia formation. This formation "underlies and is older than the moraine-fringed drift sheet of the northeastern United States."[3]

In summarizing his work on the Columbia formation, McGee[4] interpreted it as representing a first glacial epoch, as passing northward into lower till, and as separated by a long interglacial epoch from the well-known glacial deposits of the northern states, the second glacial epoch of his Conspectus, the Wisconsin glacial drift of current geological nomenclature.

Shaler, in a revision of his own work on the Gay Head section, published in 1890,[5] reaffirmed his belief in the glacial origin of the infolded conglomerate bed in the series but remained undecided between a late Tertiary and a Pleistocene date for the epoch of glaciation. In a section of the Gay Head cliffs prepared by me under Shaler's direction, the glacial gravel, sand, and associated material that lies above the Miocene and unconformably beneath the latest or Wisconsin drift are called interglacial and preglacial, and are grouped in three divisions, as follows, in ascending order:

8. Sands and clays
7. Ferruginous sands
6. Gravel and boulder beds

In this work it was shown that the glacial series in the Gay Head section, no matter how much infolded and overthrust by Miocene and Cretaceous beds, are comparable with the latest drift of the surface moraine and lie stratigraphically above demonstrable Tertiary beds. A small patch of fossiliferous sand that overlies the Miocene greensand and that was later referred to the Pliocene system was not included in the section as drawn. Shaler's paper showed that, on Marthas Vineyard, deposits essentially like the Pleistocene glacial deposits had been separated from the latest drift of the terminal moraine by long erosion. These deposits extended downward as a distinct group, separable from the determinable Miocene and the remnant of what was later shown to be Pliocene by the readily recognized characteristics of the Columbia formation of McGee.

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[1] Shaler, N. S., Geology of Marthas Vineyard, Seventh Ann. Rept. U. S. Geol. Survey, pp 336–337, 1888.

[2] McGee, W. J., Three formations of the middle Atlantic slope, Am. Jour. Sci., **35**, pp. 120–143, 328–330, 367–388, 448–466, 1888.

[3] McGee, *op. cit.*, p. 461.

[4] McGee, Conspectus of American Quaternary phenomena, *op. cit.*, p. 462.

[5] Shaler, N. S., Tertiary and Cretaceous deposits of eastern Massachusetts, Bull. Geol. Soc. America, **1**, 1890, pp. 443–452.

In 1897, in continuation of field work under the supervision of Shaler, I made a study and comparison of the sections at Clay Head on Block Island and at Gay Head on Marthas Vineyard. In a report on this work[1] I presented evidence of an epoch of erosion prior to the deposition of the earliest Pleistocene on these islands. All the beds of granitic gravel and sand in the two sections were referred to the Pleistocene because of their stratigraphic relations to the overlying glacial moraines and because of their relatively slight decomposition as compared with the quartzose and clayey sediments of the determinable Tertiary and Cretaceous beds in the basal parts of the sections. A further reason for regarding the beds of boulders and sand as glacial and Pleistocene was found in the northern origin of the glacial drift. After examining a section at Sankaty Head, on Nantucket, I grouped the beds as follows:

Pleistocene Formations, Classification of 1897

- Wisconsin frontal moraine. Last glacial epoch.
  - Vineyard interval of erosion. Last interglacial epoch.
- Tisbury beds; clay, sand, and scattered boulders.
    - Erosion interval and unconformity following the Gay Head diastrophe; now referred to ice thrust.
    - Sankaty epoch; granitic gravel and sand in folded beds carrying marine fossils on Nantucket.
- Lower boulder bed; recognized in Gay Head cliffs.

In 1901, subsequent to the work on Marthas Vineyard, I published an account[2] of the glacial deposits of the Oyster Bay and Hempstead quadrangles, on Long Island, where, below the Wisconsin moraine, an eroded surface was found representing an interval equivalent to the Vineyard interglacial stage, beneath which surface lay gravel and sand separated by a bed of till. To the whole of these deposits the name Manhasset was given, in the belief that it was a local equivalent of the "Tisbury beds" on Marthas Vineyard. The names Tisbury and Manhasset were used as local designations, for it was not considered desirable to extend the use of the names of Pleistocene deposits beyond the states in which they are found. Below the Manhasset on Long Island there was also found a blue clay, the base of which was not seen. This clay was, with some doubt, regarded as a basal part of the older Pleistocene, for which McGee's name Columbia was retained.

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[1] Woodworth, J. B., Unconformities on Marthas Vineyard and Block Island, Bull. Geol. Soc. America, **8**, pp. 197–212, 1897.

[2] Woodworth, J. B., Pleistocene geology of portions of Nassau County and Borough of Queens, Bull. New York State Mus., **48**, pp. 617–668, with colored geological map, Albany, N. Y., 1901.

Fuller's determination of the Pleistocene stratigraphy had fixed the position of the beds of laminated blue clay not only on Long Island but on Marthas Vineyard, where their relations to the Pleistocene series had not been clearly made out. It is true that in certain sections on the north shore of Marthas Vineyard I had included them in the "Tisbury beds," but in our work on the south side of the island neither I nor Shaler had satisfactorily separated these Pleistocene beds of blue clay from the Tertiary and Cretaceous beds with which they had been confounded.

Fuller's determination of the position of the beds of Gardiners clay has made it possible to fix the position of other Pleistocene beds immediately above and below them in the islands east of Long Island, and my associate, Dr. Edward Wigglesworth, has found this clay bed a satisfactory horizon marker for the older Pleistocene deposits on Marthas Vineyard.

Of the Mannetto gravel of Fuller and the unconformity succeeding it below the Maneco gravel, it may be said that different deposits are found on Marthas Vineyard in an apparently equivalent position, as explained beyond, and beneath them occur deposits that appear to be older than Fuller's Mannetto gravel. To these underlying deposits new names are here given.

CLASSIFICATION OF THE PLEISTOCENE DEPOSITS ADOPTED IN THIS REPORT

All the Quaternary deposits on the New England Islands from Long Island eastward to Marthas Vineyard and from the Jameco formation upward to the Wisconsin moraines are easily recognized and singularly persistent, but their equivalents on Nantucket and Cape Cod have not been certainly determined. Below the Jameco gravel, and certainly below the unconformity in the sections at Gay Head cliffs on Marthas Vineyard and at Clay Head on Block Island, there is a complex series of glacial deposits, mainly stratified gravel and sand, which appears to occupy, at least in part, the position in the section assigned to the Mannetto gravel on Long Island by Fuller; but these deposits cannot be correlated with any lithologic equivalent in Fuller's Mannetto deposits. The deposits agree in containing pebbles of feldspar-bearing rocks, such as granite derived from the mainland. The chert pebbles found in the Mannetto on Long Island appear to be equivalent to the chert pebbles found in the Aquinnah or osseous conglomerate on Gay Head; but this deposit contains no feldspar-bearing pebbles, and it carries remains of fossil animals that range in age from Miocene to early Pleistocene, which have not been found on Long Island. The glacial deposits on Block Island and Marthas Vineyard below the unconformity mentioned may represent the whole of the Mannetto, but they seem to begin with signs of glaciation in ice-transported boulders, which are followed by gravel and sand deposited in water long before the epoch of close folding of the preëxisting beds in those islands at the time of the Mannetto ice advance.

A striking feature of the glacial deposits on these islands is their content of undecomposed feldspathic minerals, the essential constituents of such rocks as granite, diorite, and other igneous and metamorphic rocks of the adjacent mainland on the north, from which they were derived by glaciation. The underlying deposits, including the Aquinnah conglomerate (here assigned to the oldest Pleistocene because it contains traces of a horse of that age) and the still older Miocene and Cretaceous deposits, contain no quartzite pebbles, though quartz pebbles are abundant, and none of the kinds of rock that make up the bulk of the glacial series. This lack of feldspathic deposits appears to be due to the weathering, in preglacial time, of certain beds, such as those of kaolinite, which is made up of grains of quartz and clay, the clay representing decomposed particles of feldspar.

Excluding the superficial glacial material of the Wisconsin stage, whose thickness reaches 50 feet in the more massive morainal knobs and in the gravel of the outwash plains fronting the terminal moraine, the older Pleistocene deposits have a maximum thickness in the islands of about 250 feet, as follows:

	Feet
Manhasset formation	50
Jacob sand	10 to 50
Gardiners clay	50
Jameco and Mannetto formations	50
Weyquosque formation and Dukes boulder bed	50

AQUINNAH CONGLOMERATE (OSSEOUS CONGLOMERATE)

The Aquinnah conglomerate (the osseous conglomerate of Hitchcock) is a local deposit of preglacial age. It is known only on Marthas Vineyard, where it forms a bed in Gay Head cliffs. It has already been mentioned here because it contains vertebrate remains ranging in age from Miocene through Pliocene to early Pleistocene. The bed exposed to view in Gay Head cliffs has been greatly eroded by the ice in its earlier advances. Scattered boulders of the conglomerate

Classification and Correlation of the Pleistocene Deposits of Cape Cod and the New England Islands

(Oldest formation at bottom, youngest at top)

Stage	Origin	Name, location, and distinctive features	Name applied to deposits on New England Islands and Cape Cod		Mississippi Valley classification adopted by U. S. Geological Survey
Wisconsin	Glacial	Falmouth or "inner" moraine (=Charlestown moraine of R. I. and Harbor Hill moraine of Long Island)	Falmouth moraine	Plymouth interlobate moraine	Wisconsin stage (glacial)
		Nantucket or "outer" moraine (=Ronkonkoma moraine of Long Island)	Nantucket moraine		
Vineyard	Interglacial	Characterized principally by erosion on Block Island, Marthas Vineyard, Nantucket and Cape Cod, but accompanied by some marine deposits, and locally, on Marthas Vineyard, by some beds of peat	Vineyard formation		Peorian stage (interglacial) Iowan stage (glacial) Sangamon stage (interglacial)
Manhasset	Glacial	Hempstead gravel	Manhasset formation	Hempstead gravel member	Illinoian stage (glacial)
		Montauk till. Long Island to Marthas Vineyard		Montauk till member	
		Herod gravel			
Jacob	Transitional	Sand, transitional, closing the episode of submergence	Jacob sand		
Gardiners	Interglacial	Episode of submergence, characterized by stratified marine blue clay of glacial origin	Gardiners clay		Yarmouth stage (interglacial)
Jameco	Glacial	Moshup boulder clay and certain stony blue clays of till-like texture at Nashaquitsa cliffs and No Man's Land; contemporaneous with at least upper part of typical Jameco gravel	Jameco formation	Moshup till member	Kansas stage (glacial)
		Coarse gravel, the chief deposit beneath the Gardiners clay; of typical Jameco type		Coarse gravel of typical Jameco type	
		The ferruginous boulder bed on Gay Head and its probable equivalent on Block Island at Clay Head.		Ferruginous boulder bed	
Post-Mannetto	Interglacial	Characterized by deep erosion on Long Island; correlated with the erosion interval on Marthas Vineyard and Block Island, where there is a sharp unconformity between lower folded early Pleistocene, Tertiary, and Cretaceous deposits and what appears to be base of Jameco gravel	(Not accompanied by deposits)		Aftonian stage (interglacial)
Mannetto	Glacial	Traces of glacial outwash gravel on Long Island ascribed by Fuller to an ice invasion. The strong folding at this time at Clay Head on Block Island and at Gay Head on Marthas Vineyard is attributed to thrust by the ice sheet advancing upon the coastal plain deposits. To deposition by this ice is thought to be due the stony blue clay till at Gay Head (an ice-laid till without boulders) and the overlying gravel bed	Mannetto formation		Nebraskan stage (glacial) (Probably equivalent to Jerseyan drift of New Jersey)
	Interval of glacial recession and marine invasion.	Glacial sand and gravel on Marthas Vineyard and Block Island (Weyquosque formation) and contemporaneous marine sand of Nantucket and Cape Cod (Sankaty sand)	Weyquosque formation (glacial sand and gravel)	Sankaty sand (marine sand)	
	Glacial. Possibly first advance of Mannetto stage.	Scattered boulder deposits of glacial origin; at Gay Head at base of Pleistocene section; boulder-bearing gravels, etc.; all known deposits reworked by water. Deposits largely beneath sea level except at Gay Head cliffs, Clay Head, and possibly a few other localities	Dukes boulder bed		
	Non-glacial	Preglacial conglomerate bed at Gay Head cliffs, composed of quartz and chert pebbles, with fossil bones of Miocene Cetacea, a Pliocene camel, and a Pleistocene horse; probably an old stream gravel	Aquinnah conglomerate		(No known correlative)

Unconformable on Cretaceous and Miocene.

have been found at the stratigraphic horizon of the bed elsewhere in the cliffs and farther east, in the Peaked Hill clay pits, as well as southeast of that point, near the locality known as ''Long View."

The paleontological importance of this small remnant of a deposit, which consists chiefly of vein-quartz pebbles, chert pebbles, and transported teeth of sharks and bones of cetaceans and higher mammals, without traces of such feldspathic rocks as are found in the overlying Pleistocene glacial deposits, seems to warrant its indication by a stratigraphic name. The name Aquinnah conglomerate is, therefore, here proposed, Aquinnah being a native Indian name for Gay Head.

The fossils found in the Aquinnah conglomerate have already been mentioned, except those found in certain black or at some places light-grayish chert pebbles, waterworn and smoothed, and usually not more than an inch in their largest diameter, for which no source has been found in the New England region.

The occurrence of fossils in these pebbles was announced by me in 1891,[1] but they were then erroneously referred to the Cambrian system. In a later note,[2] they were referred to some horizon as high as Silurian, on the authority of Walcott, who had examined some of the material. The fossils found consist of small species of bryozoa, tabulate corals, and pieces of crinoids.

A chert pebble found by me in the cliffs at Gay Head in the summer of 1920 was submitted to E. O. Ulrich, who recognized in it a branching species of the tubulate coral *Cladopora*. He also recognized a longitudinal section of some species of *Aulopora*, some irregular sections of some species of *Aulopora*, and some irregular sections of a bifoliate Bryozoan of the genus *Cystodictya*. He believes that these fossils may belong to a horizon as high as the lower Middle Devonian rather than to that of the Lower Devonian (Helderberg), though he notes that the New Scotland formation carries species comparable to those seen in the specimen. He suggests that this fossiliferous chert pebble may have been brought from the region near Hudson Bay or possibly from some place between the southern end of the bay and the St. Lawrence valley.[3] The suggestion appears to favor the idea that the pebbles were transported as stomach stones (gastroliths) by seals.

FIRST STAGE OF GLACIATION

The first events of the glacial epoch in this region are correlated with the Nebraskan glacial stage of the Mississippi Valley and with the supposedly contemporaneous Jerseyan drift of New Jersey. The deposits of this stage include the following beds, which are named in ascending order: (1) the Dukes boulder bed; (2) the marine Sankaty formation and the contemporaneous glacial sand and gravel here named the Weyquosque formation; and (3) the stony blue clay and overlying gravel tentatively correlated with the Mannetto gravel of Long Island.

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[1] Woodworth, J. B., Note on the occurrence of erratic Cambrian fossils in the Neocene gravels of the island of Marthas Vineyard, Am. Geologist, **9**, pp. 243–247, fig. 3, 1891.

[2] Woodworth, J. B. (with Shaler, N. S. and Foerste, Aug. F), Chert pebbles: Geology of the Narragansett Basin, U. S. Geol. Survey Mon. 33, p. 113, 1899.

[3] Abstract of a letter of J. B. Woodworth dated September 30, 1920.

DUKES BOULDER BED[1] (FIRST GLACIAL SUBSTAGE)

At the base of the glacial deposits in the section at Gay Head cliffs, and apparently at the base in Clay Head, on Block Island, there are lenticular patches of boulders and cobbles of glacial origin derived from the mainland on the north.

The deposits have yielded only one striated stone, which was found in 1889 in a huddle of small boulders resting on Cretaceous deposits in the highly folded section at Gay Head just east of the quadrangular fold. The same huddle of boulders contained rolled fragments of the near-by Aquinnah conglomerate, of earlier Pleistocene age. Elsewhere in the section at Gay Head the basal gravel, which rests on the Aquinnah conglomerate, carries isolated angular boulders of granite, many of them deeply disintegrated, and at one place a boulder weighing about eight tons was seen in 1889.

On Block Island a notable deposit of rounded and waterworn boulders lies at the base of the Pleistocene section in the overturned folds at Clay Head.

The Dukes boulder bed is evidently a discontinuous deposit of glacial origin, somewhat rearranged by the action of water. The deposit is of small extent, and is found only where the upturning of the beds has brought the basal Pleistocene above sea level. The underlying beds were apparently not disturbed by glacial thrust at the time these boulders were laid down. Probably the ice sheet did not invade the district in which the boulders are now seen; otherwise the beds containing them should have been pushed up and folded as they were during later ice advances.

The ferruginous conglomerate at the southwest end of the Gay Head section, heretofore referred by me to this horizon, is now regarded, on structural grounds, as a deposit laid down after the close folding occurred in that cliff.

The Dukes boulder bed is succeeded above by beds of glacial gravel and sand and, where boulders are absent, these form the base of the Pleistocene deposits at Gay Head and Clay Head. This gravel and sand form the next higher formation, here known as the Weyquosque.

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[1] Named from the "county of Duke's County," the quaint legal designation of the county comprising Marthas Vineyard, No Mans Land, and the Elizabeth Islands, so-called in honor of the Duke of York, to whom the islands were at one time granted.

WEYQUOSQUE FORMATION (GLACIAL)

This formation is named from exposures found for the last thirty years at the east end of Nashaquitsa cliffs, on the south side of Marthas Vineyard, at the locality known to the inhabitants as Weyquosque. In its more sandy phases the deposit has a peculiar brownish or greenish shade, its color appearing to depend upon the presence of glauconite derived from the Miocene greensand bed at the Gay Head district. The gravelly phases of the deposit contain pebbles of granite and other undecomposed feldspathic rocks. At Weyquosque (Nashaquitsa) the formation rests on a bed of fossiliferous gravel composed of débris derived from Miocene deposits, or possibly from the Aquinnah conglomerate, and from lignitic Cretaceous beds, commingled with a few pebbles of granitic and similar rocks, such as characterize the glacial series. This local basal layer is evidently of later origin than the Aquinnah conglomerate, which is of early Pleistocene age. The upper part of the bed at Nashaquitsa is cross-bedded on a large scale, and is succeeded unconformably by a bed of boulder clay. Similar deposits, also tinged with green or brown, occur on Nonamesset Island and at the base of the Pleistocene on Block Island. In the Gay Head cliffs, beds of gravel and sand occupying the same basal position give way in places to the basal deposit of coarse cobbles and boulders called the Dukes boulder bed.

In 1889 about 70 waterworn fish teeth, chiefly those of sharks, were collected at Nashaquitsa. They were evidently redeposited from broken-up beds of Aquinnah conglomerate or from Miocene fossiliferous deposits.

The beds of Weyquosque glacial sand and gravel lie essentially at the same horizon as the marine Sankaty sand of Nantucket and Cape Cod.

SANKATY SAND (MARINE)

In 1896 the gravel and sand lying above the Dukes boulder bed at Gay Head were referred to the horizon of the fossiliferous sand on Nantucket and named the Sankaty beds, because of the identical structural relations beneath the unconformably overlying Wisconsin drift and of the belief then held that the beds of fossiliferous sand at Sankaty Head are of Pleistocene age. It now appears probable that the Sankaty beds are a constituent part of the older Pleistocene deposits as here defined, and that the beds constitute a marine fossiliferous formation lying along the east coast of Massachusetts in a position equivalent to the beds of glacial sand and gravel on Marthas Vineyard and Block Island that are here named the Weyquosque formation.

In reports on investigations made long ago at Sankaty Head by Verrill and others, a bed of clay was described as lying stratigraphically below the fossiliferous sand, and the sand was described as having a pebbly iron-stained basal layer. The clay below the Sankaty sand is not so clearly described as to enable one to decide whether it is a continuation of the stratified blue clay of the Gardiners type, essentially free from glacial erratics, or an oxidized stony blue clay such as crops out at Squam Head and at points farther north on the same coast.[1] Scudder describes the underlying clay as "a thick bed of light-brown sandy clay" and says that the overlying bed of gravel and sand is four feet thick, coarsest in the upper part and more or less ferruginous, hardening on exposure to a rather compact conglomerate. This description agrees well with that of the glacial conglomerate at or near the base of the Pleistocene series in the eastern islands. The quartz-pebble conglomerate in the underlying Cretaceous deposits is not ferruginous. Furthermore, the overlying beds of fossiliferous sand carry small pebbles and particles of feldspar-bearing rock, a characteristic of the Pleistocene series as a whole and a feature not observed in beds of unquestioned Pliocene or older Tertiary sand and gravel in the New England Islands. Shaler[2] was "disposed to believe that this lower sandy clay . . . represents the upper portion of the lower till at Nantucket." Fuller, on physical evidence rather than on the evidence presented by the fossils in the Sankaty beds, correlated the sand in the Sankaty type section with the Jacob sand, which is regarded as transitional between the Gardiners clay below and the Herod gravel above.

Until recent years the marine fauna of the Sankaty section was invariably regarded as of post-Tertiary age. At one time J. D. Dana erroneously assumed that the beds are postglacial and that they form a part of his "Champlain group," but Upham showed conclusively that the beds were older than the last ice advance to the island. A detailed study of the section containing fossil shells was made during the summer of 1904 by Dr. J. H. Wilson,[3] who appears to have regarded the underlying clay as of glacial origin and "identical with the 'pre-Wisconsin till.'" Twenty-one species new to the locality were discovered, of which a number were identified by Dall. Among the newly found species were *Serripes perousii* Deshayes, *Macoma incongrua* von Martens, and *Pandora crassidens* Conrad, the first two of which had not been previously found east of Point Barrow. The form last named is common in the Miocene of Maryland. Dr. Wilson appears to have assumed that the fauna as a whole lived in Pleistocene time. He also found a single specimen of the extinct species *Chrysodomus stonei* Pilsbry.

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[1] Woodworth, J. B., The glacial brick clays of Rhode Island and Massachusetts, Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 1, ch. 2, pp. 976–977, 1896.

[2] Shaler, N. S., Geology of Nantucket, U. S. Geol. Survey Bull. 53, pp. 33–34, 1889.

[3] Wilson, J. Howard, The glacial history of Nantucket and Cape Cod, p. 90. The Columbia University Press, New York, 1906.

The occurrence of a species that is elsewhere unknown above the Miocene on the Atlantic coast and of a species of older Pleistocene age, so regarded, has to be taken with much circumspection in determining the age of the deposit. I found in the beds at Squam Head a shark's tooth of the type of *Charcarodon*, together with triturated shells, showing that the Miocene deposits there had been worked over into the overlying Sankaty beds. Again at Nashaquitsa cliffs, in 1899, I collected more than seventy fossil Tertiary shark's teeth from beds of older Pleistocene gravel, unaccompanied by other traces of organic remains. The redeposition of organic remains is common in the shore phases of several fossiliferous beds on this coast. The isolated occurrence in these beds of organic forms that are elsewhere peculiar to older strata should have little weight in determining their age.

Dr. Wilson confirms earlier observers in recognizing a lower and an upper series of layers in the Sankaty sand, characterized by faunal differences. The lower beds he described as containing prevailingly species of *Ostrea*, *Venus*, and *Mya*, along with mud crabs, an assemblage indicating shallow water protected from the open sea. The upper beds carry an Arctic fauna —*Macoma incongrua*, *Serripes laperoussi*, and *Pandora crassidens*. The association of the local newly identified species *Astarte sankatyensis* with these species in the upper shell beds led Dr. Wilson to regard it also as a cold-water form having a northern range or as one that had become extinct.

In regard to the horizon carrying *Macoma incongrua*, Dall stated[1] that he regarded this species as probably upper Pliocene; but he was under the impression that the lower beds carry this Arctic fauna, whereas Wilson states that the Arctic fauna was found in the upper beds. Although the beds at Sankaty Head are tilted, and although the same beds between that plain and Squam Head, as observed in 1915, are folded over into a vertical position, nothing has been found at Sankaty Head to warrant the belief that the beds there are overturned in such a way as to lead to the supposition that the lower one is of Pleistocene age and the upper one of upper Pliocene age. Dall wrote as follows:[2]

> There is no particular reason why *Macoma incongrua* should not be Pleistocene as well as Pliocene, since it is now living on the Pacific side. I take it that the glacial epoch cut off the intercommunication between the two sides of the continent; but there is no reason why some of the Pliocene species should not have lingered on into the Pleistocene on the Atlantic side.

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[1] Letter to J. B. Woodworth dated November 14, 1916.

[2] Letter dated November 9, 1916.

> But I am confident from the association of species that the period of close intercommunication was Pliocene, because the fauna shows a milder climate than subsequently. This is true all around the northern hemisphere.

The fauna of the Gardiners clay, as shown by Fuller and Veatch, is that of an interglacial stage that occurred long after the beginning of the Pleistocene epoch. In the Long Island region, this clay has afforded the following species, listed by Fuller:[1]

Anomia ephippium
Baccium obsoletum
Crepidula fornicata
Cyprina islandica
Mya arenaria
Mytilus edulis
Modiola sp.
Nassa trivittata
Ostrea virginica
Purpura lapillus
Venus mercenaria
Solen ensis

Shells of *Pecten*, fragments of an echinoderm, of *Mullinia* and *Astarte*, have also been either reported or identified.

The Jacob sand, which overlies the Gardiners clay, at least from Gay Head westward, has yielded no fossils on Block Island or Marthas Vineyard. Fuller[2] refers the Sankaty Head section to this horizon and notes Sanderson Smith,[3] in 1867, collected a marine fauna from the Jacob sand on the east side of Gardiners Island.

The fauna of the Jacob sand in the western part of the New England Islands, according to Sanderson Smith, is almost entirely molluscan, as follows:

Anthozoa:
  A small coral
Gasteropoda:
  Tornatella punctostriata Adams
  Bulla canalicula Gould
  Fusus decemcostatus Say
  Purpura lapillus Lam.
  Nassa trivittata Say
  Nassa vibex Say
  Columbella unata Sowerby
  Chemnitzia interrupta Stimpson
  Crepidula unguiformis Lam.
  Crepidula fornicata Lam.
  Natica duplicata Say
  Natica heros or *triseriata?*
Pelecypoda:
  Arca transversa Say
  Arca pexata Say?
  Ostrea borealis Lam.
  Pecten islandicus Chemn.
  Pecten magellanicus Lam.
  Cardita borealis Conrad
  Astarte sulcata Fleming
  Lucina radula Gould?
  Venus mercenaria Linn.
  Mactra lateralis Say
  Mya arenaria Linn.

Crustacea:
  Balanus, fragment

Fuller credits Veach with collecting from the same section the following additional species, identified by Dall:

Chrysodomus pygmaeus Gould
Astarte elliptica Brown
Cyprina islandica Gmelin
Thracia conradi Couthouy

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[1] U. S. Geol. Survey, Prof. Paper 82, pp. 104–106.
[2] Fuller, M. L., U. S. Geol. Survey Prof. Paper 82, pp. 113–114.
[3] Smith, Sanderson, Ann. N. Y. Lyceum Nat. Hist., **8**, pp. 149–151, 1867.

Sanderson Smith recognized the northern aspect of these forms from Gardiners Island, of which Dall recently remarked:

> The material appears to be practically identical from both localities and to represent the fauna now existing in the Gulf of Maine or on the coast north of Cape Cod, a little colder water being indicated than is now found south of the Cape.

The fauna agrees with that of the upper beds in the Sankaty sand on Nantucket in denoting colder water, and Fuller,[1] in his report on Long Island, refers the Sankaty sand to the horizon of the Jacob sand.

Of the species identified by Sanderson Smith and named in the above list as coming from the Jacob sand, the following have been identified from the Sankaty sand:

Crepidula fornicata
Neverita (Natica) duplicata
Lunatia (Natica) heros or *triseriata*
Arca transversa
Pecten magellanicus
Venericardia (Cardita) borealis
Venus mercenaria
Mya arenaria

Aside from *Pecten magellanicus* and associates of *Venericardia (Cardita) borealis*, the peculiar northern fauna of Pacific types in the upper part of the Sankaty sand is not found in the Jacob sand. As the Jacob sand lies near the middle of a great series of Pleistocene deposits of glacial origin (either as originally deposited or through the rehandling of the material during submergence) it should not be correlated with the Sankaty sand because of a similarity in the marine fauna brought about by cooler water, for such changes of temperature must have occurred as many times as ice sheets advanced. Furthermore, the physical evidence on Cape Cod and Nantucket as to the stratigraphic position of the equivalents of the Gardiners clay and Jacob sand indicates that the Sankaty sand underlies both these Long Island formations as well as the Jameco gravel. The probable representatives of the Gardiners clay and overlying Jacob sand of Long Island are, as Fuller first noted, found in the "clay pounds" of Highland Light and in the overlying yellow sand beneath the lighthouse. The shell-bearing Pleistocene beds encountered some 200 feet below sea-level in borings at Provincetown probably belong to a formation lower than the entire section in the outer cliffs of Cape Cod and are nearly in the position of the Sankaty sand. The Sankaty sand is, therefore, here regarded as a fossiliferous facies of a marine shallow-water deposit laid down along the east coast of Massachusetts during the first interglacial stage, in a stratigraphic position equivalent to that of the glacial sand and gravel of the Weyquosque formation, which contains no contemporaneous fossils on Marthas Vineyard and Block Island.

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[1] Fuller, M. L., Geology of Long Island, U. S. Geol. Survey Prof. Paper 82, p. 114.

MANNETTO FORMATION (GLACIAL)

High up in the folded beds in the cliff at Gay Head, on the sides of the hollow called the Devil's Den, there are exposures of a bed of compact blue clay containing small, angular fragments of rock and rounded pebbles. The bed is unstratified, having the massive character of a bed of till, and has not been well exposed within the last thirty years. In the part of the cliff northeast of the Devil's Den it lies above the horizon of the Dukes boulder bed and of the gravel bed that overlies it. Above the bed of stony blue clay other beds of glacial gravel form the high point back of the "quadrangular fold" of Hitchcock's report. The bed of stony blue clay exposed southwest of the Devil's Den is not at the same horizon.

At a point on the north shore of Marthas Vineyard near Makoniky, beds of similar stony blue clay crop out under the stratified Gardiners clay. As beds of glacial till containing large boulders occur beneath the Gardiners clay on No Mans Land and at the east end of the Nashaquitsa cliffs, in the district known as Weyquosque, the beds of stony blue clay at Gay Head probably also lie below the horizon of the Gardiners clay. Elsewhere beneath the Gardiners clay there is the bed of coarse glacial gravel that Fuller called the Jameco gravel. The gravel above the stony blue clay at Gay Head may be of early Jameco age, but in the good exposures it is separated from the Jameco by an angular unconformity — that is, it was not deposited when the folding occurred that has given to the section at Gay Head its puzzling structure. The stony blue clay (till) and the overlying bed of gravel are infolded in the section at Gay Head and are, therefore, both referred to the Mannetto glacial stage.

FOLDING AT GAY HEAD

The principal evidence of an advance of the ice at this stage in the formation of the Pleistocene deposits on Marthas Vineyard is found in the folding and overturning of all the preceding deposits. On Gay Head the displacement was an overthrust toward the southwest, which produced isoclinal folds and a consequent northeasterly dip of the beds. The stony blue clays already described indicate the presence of either land ice or floating ice prior to the folding of the glacial sands and gravels and of an unknown thickness of Tertiary deposits and underlying Cretaceous clay. An exactly comparable section may be seen in Clay Head, on Block Island. It seems probable that a great glacier advanced southward on to the deposits of the Coastal Plain at this time. This glacial advance appears to be that which Fuller inferred from the presence of the coarse Jameco gravel, a deposit of stratified material, probably formed about the front of the ice sheet before, during, and after the end of the advance of the ice.

The beds that were at this time thrown into close folds in the high ground at Gay Head on Marthas Vineyard and at Clay Head on Block Island strike generally from northeast to southwest, the direction of the main axis of the islands, except those at Gay Head, which strike more nearly from northwest to southeast, giving a northeasterly dip to the isoclinal and overturned folds in that area. The low land between Gay Head and the western part of Marthas Vineyard, east of Menemsha Pond, occupies an angle between the two local lines of structural trend and appears to have been a place of maximum forward thrust by the ice. The general direction of the motion of the ice appears to have been normal to the general strike. The boulders and small pieces of Cumberland iron ore (peridotite) found on Gay Head must have been carried about the time of this dislocation from Iron Mine Hill, in Cumberland, R. I., along a line bearing S. 47° E., a line more nearly southeast than that followed by the ice of the Wisconsin stage.

The mass of Cretaceous beds on Marthas Vineyard that was then disturbed by ice was apparently much larger than any mass subsequently disturbed. This maximum effect might well be expected at the first strong advance of the ice, for at the subsequent advances the deposits would have been pushed into attitudes that would not strongly oppose the overriding ice. Nevertheless, the beds of Gardiners clay and the later Manhasset deposits on the south shore and on Block Island were notably displaced in more or less broad and open folds produced either at the time the Montauk till was laid down or much later, beneath the first Wisconsin ice sheet.

POST-MANNETTO INTERGLACIAL STAGE

Fuller's term post-Mannetto is here applied to the interval of erosion represented by the unconformity between the eroded edges of the first folded beds at Gay Head, on Marthas Vineyard, and at Clay Head, on Block Island, and the overlying nearly horizontal beds of boulders and gravel at those places. Only small exposures of this unconformity are seen, such as those in the southern part of the section at Gay Head. Some of the beds on Block Island were folded after the larger features of the structure had been developed and overthrust faults on Gay Head broke the continuity of the plane of the unconformity. It is not known whether the deformation is due to the continuance of the action of the glacier or to subsequent action by the water of streams or of the sea. The immediately overlying bouldery gravel beds at Gay Head and Clay Head were afterward deposited on the eroded surface. The unconformity represents the removal of an unknown thickness of folded beds of clay, gravel, and sand. The overlying beds of gravel show no signs of marine action, but they contain rolled fragments of the Cretaceous and the Miocene deposits of the district, together with hardened nodules of clay such as are laid down on the beds of lignite through secular rain wash. In most of the region here considered the unconformity now lies below sea level or is not exposed. In some areas on Gay Head the section including the unconformity was worn away by erosion prior to the deposition of the Wisconsin till.

JAMECO STAGE OF GLACIATION

Jameco Formation

Ferruginous Boulder Bed. The most significant bed of boulders in the older Pleistocene deposits at Gay Head is exposed on the west side of Gay Head cliffs from the Devil's Den southward, where it lies unconformably on eroded and folded Cretaceous beds and the infolded glacial gravels of the Weyquosque formation. The bed consists mainly of boulders of granite and diorite, 3 or 4 feet in diameter, but contains a large variety of smaller stones, derived from the bed rock of southeastern Massachusetts, as well as some cobbles and pebbles of clay cemented by iron oxide. The iron has penetrated only the outer part of some of these cobbles, so that when they are broken their central parts wash out, leaving rounded cavities. The boulders and pebbles appear to be waterworn and show no striations due to glaciation, yet the coarseness of their materials, their commixture, the direction in which they have been transported, and their associations indicate that they were brought to their present positions by an ice sheet that carried them many miles south of their parent ledges. Whether the boulders and gravel were directly deposited by water that worked over deposits of till in place, or whether they were washed out of more ancient beds is not known. The deposit is probably equivalent to a part of the Jameco gravel of Fuller, and it is so classified in this report. It forms the local base of what appears to be a less disturbed series of beds deposited about Gay Head in Jameco time, prior to the deposition of the Gardiners clay. At Clay Head, on Block Island, very similar boulder beds lie unconformably upon high folded older Pleistocene and Cretaceous deposits; but the conglomerate there is less ferruginous than at Gay Head.

Coarse Gravel of Jameco Type. Typical glacial gravel, usually coarse, and consisting of a great variety of small erratics derived from the mainland on the north, is seen in the islands east of Long Island. It resembles the typical Jameco gravel of Fuller, the type occurrence of which was stated by him to be on Long Island, New York. The deposit was interpreted by him as indicating an advance of the ice, but he reported no till or signs of direct ice action.

Many of the beds are ferruginous, and some have a thickness of twenty feet or more. This gravel lies beneath the Gardiners clay in Mohegan bluffs, on the south side of Block Island; on the south side of No Mans Land; and in Nashaquitsa cliffs, on the south side of Marthas Vineyard. Probably the gravel beneath the clay at Highland Light, on Cape Cod, are at this horizon.

The typical Jameco gravel appears to be a stream deposit like those washed out from glacial fronts in low grounds or near the sea at the present day.

Moshup Till Member. A remarkable upturned bed of boulder clay that was exposed in Nashaquitsa cliffs, on Marthas Vineyard, for a quarter of a century prior to 1916, occupies, at least in part, the stratigraphic position that is elsewhere held by the Jameco gravel. It lies below the Gardiners blue clay and above the beds of sand and gravel that are here called the Weyquosque formation. (See Fig. 12 and Plate 23). On No Mans Land a similar boulder bed was exposed in 1915 and 1916 beneath the Gardiners clay. These deposits of true boulder clay confirm an inference drawn by Fuller from the occurrence of the Jameco gravel—that the deposition of the Gardiners clay was preceded by a glacial invasion and that the Jameco gravel is a product of that invasion. At one place on the north shore of Marthas Vineyard, as already noted, a bed of stony blue clay lies beneath the Gardiners clay. The exposures showing the position of this bed and of its supposed correlative beds of stony clay indicate that it replaces locally the upper part or all of the Jameco gravel and lies immediately below the stratified Gardiners blue clay. In Nashaquitsa cliffs the bed is less than ten feet thick. It is decisive evidence of the second stage of glaciation on Marthas Vineyard. Fuller found no equivalent till on Long Island, and it has not been observed on Block Island. It has not been certainly recognized east of Marthas Vineyard.

In conformity with the example set by Fuller in giving the name Montauk till member to the bed of boulder clay that divides the Manhasset formation on Long Island, this bed of till is here called the Moshup till, from the name of a local god in the aboriginal folklore concerning the origin of Gay Head. Like the Montauk till, it is not a continuous sheet.

GARDINERS INTERGLACIAL STAGE

Gardiners Clay

Distribution and character.— Beds of a dark blue clay, which are usually folded, are exposed at several places on the islands from Marthas Vineyard westward and are seen in the "clay heads" on Cape Cod. These beds, which are now correlated with the Gardiners clay, were once regarded as Tertiary or Cretaceous, an error due to the occurrence of certain beds of lignitic Cretaceous clay containing fossil plants in Nashaquitsa cliffs at places where the Gardiners clay and the glacial gravel below it and the sand above it are now extensively exposed. Fuller and Veatch showed that this bed of clay lies above a series of beds of gravel that are not distinguishable from the beds of glacial gravel on Long Island and elsewhere to the east through the New England Islands wherever the base of the uppermost bed of blue clay containing no boulders or gravel is visible.

The correlation of the beds of blue clay on Nantucket with the lenticular beds of blue clay on Cape Cod is doubtful, principally because of the improbability that a series of glacial deposits would persistently maintain parallelism, but the field study has afforded no ground for a better correlation. The difficulty of correlation is greatest where the clay occurs as lenses in gravel, as it does at Highland Light, on Cape Cod, though it may be overlain by a bed of fine sand, such as is found on the islands to the southwest.

The Gardiners clay is dark blue or, in places on Long Island, blackish; its color there being due to lignite. It contains some lignite also on Marthas Vineyard, derived from underlying Cretaceous beds, which were turned up at the time of the post-Mannetto folding and erosion. Some of the dried clay has a whitish cast, due to the presence in it of fine grains of quartz. Although certain sections contain thin layers the clay is generally massive and was apparently laid down in quiet water off the shore of a shallow sea.

At a few localities, as on the north coast of Marthas Vineyard east of Menemsha Creek, the clay is "banded" or laminated. Sayles[1] has presented evidence that such lamination is due to the changes in the conditions of deposition from winter to summer. In deposits of clay laid down on the sea floor it might be expected that the heavier wave action in winter would produce coarser beds in a zone at a given distance from the shore than those formed in the zone in summer, and that the round of the seasons would be registered in an alternation of coarse and fine material, as shown by Baron Gerard de Geer. The banding, however, is not generally so distinct in marine as in fresh-water deposits.

Fossils and origin.— The marine origin of the Gardiners clay is proved by fossils found in it at the type locality on Gardiner's Island.[2] According to Fuller's list the following species are essentially identical with those now living in the sounds along the same coast:

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[1] Sayles, R. W., Seasonal deposition in aqueo-glacial sediments, Memoir Mus. Comp. Zoöl., **47**, pp. 1–67, pls. 16, February, 1919.

[2] Fuller, M. L., Geology of Long Island, U. S. Geol. Survey Prof. Paper 82, pp. 104–106, 1914.

Gastropods:
  Nassa obsoleta
  Nassa trivittata
  Crepidula fornicata
  Purpura lapillus
Pelecypods:
  Ostrea virginica
  Mya arenaria
  Venus mercenaria
  Mytilus edulis
  Anomia ephippium
  Cyprina islandica
  Arca cenella
  Solen ensis

To this list should be added *Modiomorpha nigra* Gray ? of Dall's list of fossils found in Miocene beds on the south side of Marthas Vineyard.[1] This species was found in the gray clay now known as the Gardiners clay, of Pleistocene age. This is the only marine fossil found in the Gardiners clay east of Long Island.

This assemblage of forms indicates the marine origin of the Gardiners clay under conditions not unlike those which prevail in the shallow water of sounds or interisland passages off a continental coast that is being rapidly attacked by waves carrying particles of boulder clay, which is being laid down in successive offshore zones in the form of sheets of gravel, sand, and clay. Although isolated cobbles and thin lenses of gravel are found on Block Island and elsewhere in beds of clay that appear to be members of the Gardiners clay, probably as deposits from floating ice in winter, that clay was doubtless laid down during an interglacial stage, when glacial action was reduced to a minimum.

Until the Gardiners clay has been definitely correlated with the older glacial clay in the lower Hudson valley and in the New Haven region, as well as with the clay in the valleys of the Charles and Mystic Rivers about Boston, the attempt to determine the depth and extent of the submergence in Gardiners time must remain uncertain. The folding and the deformation of the beds of clay in the islands off the south coast preclude the use of the ordinary stratigraphic methods of estimating the initial dip of the formation and projecting the position of the shore line. At Highland Light, on Cape Cod, beds of clay that are regarded as probably of the same age rise about 120 feet above the present sea level and are only slightly deformed. The submergence at that place may have exceeded 120 feet. The beds of glacial brick clay near Belmont, northwest of Boston, which are probably older Pleistocene deposits, show an eroded surface at a height of about 120 feet above sea level. If the Gardiners clay and the correlative deposits were laid down in water that was not more than 100 fathoms deep, a reasonable assumption, there should have been formed at the same time, between them and

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[1] Dall, W. H., Am. Jour. Sci., **48**, p. 297, 1894.

the shore, a zone of gravel and sand that was swept seaward by the undertow and by offshore currents. Any such broad zone of gravel and sand laid down upon the lowland of eastern Massachusetts and southern Rhode Island during Gardiners time would have been eroded and masked by the action of succeeding ice sheets, but thick beds of gravel and sand may have been here and there redeposited in kames and sand plains at later stages of the ice. A great mass of stratified sand remains on the irregular slope between the upland at Worcester and the lowland along the coast between the 200-foot and the 400-foot contour line, but nothing is known to warrant the reference of any part of this sand to the Gardiners stage. In the Champlain valley, at the end of the last or Wisconsin glacial stage, beds of marine clay were laid down beneath as much as 400 feet of water, or, if Fairchild's estimates are correct, under more than 600 feet. The distribution of the Gardiners clay indicates that the marine invasion then may have covered the eastern lowland of Massachusetts as far west as longitude 71° 30′.

Where the Gardiners clay lies between beds of gravel and sand, the fall of the clay in cliffs where it is undercut by the sea presents for a time a steep escarpment, and landslides carry great masses of clay out over the beach, leaving scars in the cliff.

JACOB TRANSITIONAL STAGE

Jacob Sand

Upon the Gardiners clay in the New England Islands lie beds of fine sand that range in thickness from 5 to 50 feet. This sand was derived from granitic rock and in mineral composition is like the finer wash found at some places on the mainland, except that here and there it has assumed yellow and orange colors, due to the decomposition of iron oxides and their redeposition in another form in lower parts of the bed, particularly just above the impervious Gardiners clay, where some crusts of iron were formed and are exposed at the edges of the beds in sea cliffs. The type locality of this deposit, described by Fuller, is at Jacob, on Long Island. Good sections of it are exposed in Mohegan bluffs, on the south side of Block Island, as well as on the south shore of No Mans Land and at Nashaquitsa cliffs, on Marthas Vineyard. Much of the fine sand that lies beneath the moraines on the island of Naushon may occupy this horizon. The Jacob sand is exposed also above a small head of Gardiners clay at Sachem Spring, in Sherburn bluffs, west of the town of Nantucket. Beds of precisely similar sand overlie a bed of blue clay, tentatively referred to the Gardiners formation, in the bluffs at Highland Light, on Cape Cod. On the mainland farther north, in Third Cliff, south of Scituate, disturbed beds of orange-colored sand occur above blue clay that probably belongs to the Gardiners formation.

The Jacob sand, which was laid down during the retreat of the Wisconsin ice front, lies between the Gardiners clay below and the Herod glacial gravel above and probably marks the retirement of the sea after its maximum submergence of the land in Gardiners time. The formation contains no fossils, unless the marine beds at Sankaty Head, on Nantucket, belong to it. These beds, however, for reasons given, are here referred to a much lower horizon in the Pleistocene.

The Jacob sand has not been certainly identified on the mainland north and west of Scituate, but certain beds of fine sand in Boston Harbor encountered in boring may belong at this horizon. If the beds of glacial brick clay of the Mystic valley are extensions of the Gardiners clay, the Jacob sand in that region has been removed by erosion.

Assuming that the altitude of the area at Highland Light, on Cape Cod, has not been changed with reference to the bed rock of the mainland, the altitude of the nearly horizontal bed of sand in that area that probably represents the Jacob sand may indicate its altitude in the New England Islands prior to the deformation of the beds. The formation at Highland Light ranges from about 120 to 140 feet above present sea level, an altitude which, allowing for a rise of the sea floor in Jacob time, would carry the formation well on to the lowland of the eastern counties of Massachusetts south of Boston. The shore line in Jacob time may, therefore, have lain on the present lowland rather than off the present coast.

MANHASSET STAGE OF GLACIATION

Manhasset Formation

The deposits of the third stage of glaciation are here grouped under the name Manhasset formation. They occupy the geological position to which the "Tisbury group" on Marthas Vineyard had been assigned, but the "Tisbury group" had been defined so as to include certain beds of Gardiners clay and to exclude others.

Character and subdivisions.— As described by Fuller, the Manhasset formation consists of the following three members, here arranged in stratigraphic order from top to bottom:

Hempstead gravel member
Montauk till member
Herod gravel member

The typical localities of these three beds are on Long Island. The beds are well exposed in the contorted sections on the south shores of Block Island, No Mans Land, and Marthas Vineyard, but they have not been identified with certainty north and east of Marthas Vineyard. Where a series of beds of like character lies in more or less rhythmic succession, it is uncertain which member is present, unless a fairly complete section is exposed. From bottom to top the series consists of deposits made by torrential streams that poured sand and gravel (the Herod gravel) out from the front of an advancing ice sheet. Upon these beds were deposited the till laid down by the ice sheet, and finally the beds of outwashed gravel laid down over the same region during the retreat of the ice front. Viewed in this light the deposits are the product of a single stage of glaciation corresponding to the Manhasset of Long Island.

The Manhasset formation has suffered less deformation from ice thrust than any of the older divisions of the Pleistocene series in the islands, but in western Marthas Vineyard and on No Mans Land its beds are strongly folded.

Herod gravel member.— Much of the gravel of the Herod member is coarse, the largest cobbles measuring 6 inches or more in diameter, but at some places the deposit is prevailingly sandy. The beds are 5 to 10 feet thick and have not been disturbed by the deposition of the overlying Montauk till, though that till and all the underlying beds have been in places much folded by the action of ice subsequent to the deposition of the Manhasset beds. From analogy with other beds of glacial gravel, it is presumed that the Herod gravel was laid down in the open air on plains of the Jacob sand just at or above sea level. On the southwest coast of Marthas Vineyard and thence westward to places on Long Island the beds of gravel at this horizon are readily recognized in the sections, where they lie between the Jacob fine sand and the boulder-bearing beds of the Montauk till. The beds of sandy gravel seen near the tops of bluffs on Nantucket, overlying a fine sand taken to be the Jacob sand, may be eastward extensions of the Herod gravel, but the sections are not well exposed. The bed has not been certainly identified on Cape Cod, nor has it been recognized about Boston, though certain thin gravels in Third Cliff, near Scituate, are thought to belong at this horizon.

Montauk till member.— On Long Island a well-defined bed of boulder clay lies near the middle of the Manhasset gravel and here and there shows a lateral passage into layers of assorted gravel and small boulders. At Montauk Point, on Long Island, the till is thicker and was traced to Block Island and Marthas Vineyard. On western Long Island there is a boulder bed that is at few places more than 5 feet thick, but farther east, in Mohegan bluffs, on the south coast of Block Island, the till is 30 to 40 feet thick and carries some boulders that are over 6 feet in diameter. In parts of the cliffs there appear to be two beds, separated by assorted gravel, indicating two advances of the ice, as at the Wisconsin stage, but this appearance may prove to be due to repetition of the same bed by overthrust. Similar beds of boulder till are seen in the bluffs on the south side of No Mans Land, but in the western part of Marthas Vineyard, owing either to the poor exposures of the Manhasset or the thinness of the till and the associated beds of gravel, the deposit is less well defined. North and east of Marthas Vineyard the till, or boulder bed, has not been recognized, but the reported occurrence of boulders in the beds of clay encountered in the Cape Cod Canal near its east end, and again in the lower part of the beds of clay in West Barnstable, on the north side of the lower arm of the Cape, makes it seem probable that the Montauk till, rather than the lower and older Gardiners clay may occur there near sea level. The known facts concerning the till between eastern Long Island and Marthas Vineyard indicate that the ice which produced this deposit was in the form of a lobe whose axis lay over Rhode Island and eastern Connecticut.[1]

The Montauk till can be distinguished from the Wisconsin till of southeastern New England by its large content of blue clay. No similar boulder clay is found in the Wisconsin drift in southeastern Massachusetts. The great amount of clay in the Montauk till may be due in part to the erosion of the underlying Gardiners clay, which probably overlapped far upon the lowland of southern Massachusetts and Rhode Island and to a less extent upon southern Connecticut, though not in less thickness in the narrower lowlands of the river valleys and in the Triassic lowland about New Haven.

The outer limit of the Montauk till is unknown. The ice sheet evidently extended beyond the site of the outer New England islands, as did also the other members of the Manhasset formation, but the action of the sea has commingled on its floor the materials of numerous glacial deposits. The large boulders indicated on old charts of the Nantucket shoals near the site of the modern lightship show that one or more of the Pleistocene ice advances reached a latitude nearly 50 miles south of the present south coast of Marthas Vineyard.

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[1] Woodworth, J. B., Pleistocene geology of the Oyster Bay and Hempstead quadrangles on Long Island, N. Y. State Mus. Bull. 48, pl. 1, Albany, 1901. On use of name "Tisbury beds" to include equivalent deposits on Marthas Vineyard, see Woodworth in Seventeenth Annual Report United States Geological Survey (1895–96), pt. 1, pp. 977–978, 1896, correlation table facing p. 988. As originally defined, the "Tisbury beds" prove to have included formations from the Gardiners clay to the top of the Manhasset formation as now defined. References to the Montauk till are made by Fuller, M. L., Probable pre-Kansan and Iowan deposits on Long Island, N. Y., Am. Geologist, **32**, pp. 308–311, 1903; Glacial stages in southeastern New England and vicinity, Science, **24**, pp. 467–469, October 12, 1906; The geology of Long Island, U. S. Geol. Survey Prof. Paper 82, pp. 132–149, 1914. Also Veatch, A. C., Outlines of the geology of Long Island, U. S. Geol. Survey Prof. Paper 44, pp. 41–43, 1906.

The boulders in the Montauk till, which were embedded in impervious clay; are fairly fresh looking. Many of them are less weathered than the Wisconsin boulders, but what number of them were wrested from ledges during the Manhasset ice invasion and what number were derived from older deposits of till cannot be determined, for many of the larger boulders in pre-Montauk beds are but slightly weathered.

The lithologic character of the boulders in the Montauk till is practically identical with that of the boulders in the Wisconsin drift. The greater part of the boulders and larger cobbles on the beaches of the south coast of Block Island, No Mans Land, and Marthas Vineyard were probably derived from the Montauk till, and where that till has been folded and its beds have been eroded the large boulders now found on the surface may be residual blocks that were transported for short distances and redistributed, especially by the later Wisconsin ice sheet, into which they would have been incorporated and commingled with boulders derived from the mainland.

Nothing seen in the Montauk till indicates that the land was then submerged; indeed the beds of coarse gravel immediately above and below the till indicate that the places at which these deposits are found may have stood anywhere from just at sea level to any elevation above the sea. In other words, the deposition of the entire series of Manhasset beds appears to have involved no action of the sea.

Hempstead gravel member.— On Long Island deposits of glacial gravel and sandy gravel lie upon the Montauk till in the gravel pits at Hempstead, and thinner beds of similar gravel or sandy gravel may be seen here and there above the Montauk till along the coasts of the islands as far east as Marthas Vineyard. If the beds of bouldery clay about Barnstable, on the bay side of Cape Cod, are also of Montauk age, as seems probable, the beds of gravel overlying the deposit there are extensions of the Hempstead gravel.

The Hempstead gravel is the natural successor of the boulder bed, for during the retreat of the ice front across a field of subglacial till streams would at once flow out upon the surface and deposit the drift washed out from the melting ice. Farther south sand and still farther out clay might be deposited.

The gravel at this horizon appears to be the last remaining deposit laid down in this region above sea level before the Wisconsin ice advance; but in the interval between the disappearance of the Manhasset ice sheet and the advance of the first Wisconsin ice sheet in the outer islands there was a long period of stream erosion, and probably higher beds of the Manhasset formation, such as beds of outwash glacial sand, were removed.

VINEYARD INTERGLACIAL STAGE

The Vineyard interglacial stage probably covers the time of the following events in the Mississippi Valley, in chronologic order: Sangamon interglacial stage of Leverett, Iowan stage of glaciation of Iowa geologists, and Peorian interglacial stage of Leverett.

The Wisconsin drift lies unconformably upon all the Pleistocene and older formations already described. Shaler appears to have recognized an eroded old land surface of pre-Wisconsin date in his report on the geology of Marthas Vineyard, when he still regarded the pre-Wisconsin drift and the older formations of the island as Tertiary. He writes:[1]

> The form of the surface of the Tertiary [sic] beds compels me to believe that they retain in good part the shape which they had before the beginning of the last glacial period. If we could remove all the glacial waste from this surface we should find that it had a contour closely resembling that of the chalk downs in southern England. We should see broad, rolling hills sloping gently down to infrequent valleys, a topography characteristic of a land surface where rain, frost, and stream had long and steadily acted upon beds of the uniform nature which characterizes the Vineyard series.

In 1897 Shaler again described this erosion surface, giving additional information gained from a resurvey of the island. Its date was fixed as later than that of the deposits here described as the Manhasset formation and earlier than the Wisconsin stage. He assigned not only the erosion of the valleys in the uplands of Marthas Vineyard to pluvial action at this stage but also the excavation of the neighboring sound; and he estimated that the time indicated by this erosion was twenty times as long as the interval between the present day and the disappearance from the island of the last ice sheet.[2]

In 1897 I presented further evidence relating to the epoch of interglacial erosion that preceded the Wisconsin moraine, showing the beheadal and capture of streams and the partial adjustment of streams to the folding of the older beds on Marthas Vineyard, and I proposed the name *Vineyard interval* for this epoch.[3]

In the same paper traces of the Vineyard stage of erosion by running water were reported to be recognizable beneath the drift and traces of the action of Wisconsin ice on Block Island. Still later, in 1901, the same erosion surface was recognized on the north shore of Long Island in the towns of Oyster Bay and North Hempstead, where a terrace north of the terminal moraine, at an elevation of about 200 feet, composed of the Manhasset formation, was eaten into on the north by streams that drained into the sound, whose valleys were later occupied by the Wisconsin ice sheet.[1]

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[1] Shaler, N. S., Report on the geology of Marthas Vineyard, Seventh Ann. Rept. U. S. Geol. Survey, p. 328, 1888.

[2] Shaler, N. S., Tertiary and Cretaceous deposits of eastern Massachusetts, Bull. Geol. Soc. America, **1**, p. 448, 1890.

[3] Woodworth, J. B., Unconformities of Marthas Vineyard and of Block Island, Bull. Geol. Soc. America, **8**, pp. 208–209, 211–212.

Similar topographic features are seen at Vineyard Haven, in the eastern part of Marthas Vineyard, and in other partly drift-masked valleys on that island, as well as on the south side of Cape Cod near Chatham. Correlated with these features in time is a narrow, moraine-covered bench on the north side of Marthas Vineyard, which is probably a remnant of a terrace that stood at an altitude of about 150 feet. Remnants of such a surface are recognizable in the southeastern part of Cape Cod peninsula, beyond the outwash and drift of the Falmouth moraine, as well as in the highlands of Truro.

Large tracts of glacial and older deposits laid down in the eastern islands before the Vineyard stage present surfaces about 100 feet above the present sea level. Such a surface is well displayed at the eastern side of Marthas Vineyard, where it merges into the "outwash" plain of the Nantucket substage of the terminal moraine. Nantucket island appears to have been leveled before or during the Wisconsin stage, so that now only one point on it attains an altitude of 100 feet. Southern Cape Cod appears also to have been reduced before Wisconsin time to levels below 100 feet above the present sea level.

After the terraces that now stand at altitudes between 60 and 100 feet were formed there was an uplift of the land, which was followed by the excavation of valleys on the north side of the eastern islands of the group. Something like a common expression is seen in the narrow coves about Hempstead Harbor and Oyster Bay, on Long Island, and those in Lagoon and Vineyard Haven Harbor and Chappaquonsett and James Ponds, on Marthas Vineyard. The valleys that drain into the sounds north of them appear to have been formed just before the advent of the first Wisconsin ice sheet. On the isostatic hypothesis a depression of the earth's crust by a great regional glacier such as covered northeastern North America should have been compensated in the zone of the ice front by a negative deleveling[2] that increased the effect of the withdrawal of water from the oceans to form the ice sheets through snowfall.

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[1] Woodworth, J. B., Pleistocene geology of portions of Nassau County and the Borough of Queens, N. Y. State Mus. Bull. 48, pp. 634–637, Albany, 1901. With colored geological map, pl. 1.

[2] Delevel, to change the level of a body, as of land in relation to sea level, or vice versa. Cf. French *denivellement*, for which deleveling is an exact equivalent, defined as a change of level. The terms negative and positive are used in this connection in the sense proposed by Edouard Suess in "La Face de la Terre," in accordance with the mode of stating tidal measurements by hydrographers. See note on the term deleveling in Bull. Mus. Comp. Zoöl., geol. ser., **31**, p. 100, 1912.

The geological and biological evidence available in the New England Islands indicates that the land there was higher than now during the stage of the first Wisconsin or Nantucket moraine, and that it afterward sank to its present level. The rise before the end of the Wisconsin stage and the subsequent sinking of the land are in accordance with glacial theory and the doctrine of isostasy. The tract submerged during glaciation should be occupied by glacial cover during the retreat, when the marine clays of the retreatal stage would be laid down. The laminated blue clay of the Gardiners stage appear to have been laid down on such a tract. The marine Sankaty sand, laid down after an early ice invasion, if correctly understood, bears a similar relation to the margin of the ice sheet, whose terminal moraine probably lay south of Marthas Vineyard and Nantucket.

The late Pliocene and Pleistocene terraces in Maryland show a progressive uplift of the continent during the period of their formation. The history of the terraces on the islands from the late Vineyard stage onward shows that, despite occasional depression below sea level, uplift has here also prevailed, but the terraces in Maryland[1] that stand above the present strand may be of pre-Wisconsin age.

WISCONSIN STAGE OF GLACIATION

General Relations

The general position and leading features of the terminal moraines in southern New England have long been known, but recent surveys have considerably modified the earlier views regarding the western extension of the moraine on Nantucket and of that on Cape Cod, and have reduced the estimates of the thickness of the drift laid down by the Wisconsin ice. The estimated thickness of the Wisconsin drift is here still farther reduced, and certain knob-and-basin areas that were formerly regarded as Wisconsin moraines of indefinite thickness are here attributed to the deformation of older beds.

The Wisconsin glacial deposits here considered lie in two distinct areas. The earliest deposit is an ''outer'' terminal moraine, here named the Nantucket moraine, seen on Nantucket, Chappaquiddick, Marthas Vineyard, No Mans Land, and Block Island, and extending westward from Montauk Point, on Long Island, as the Ronkonkoma moraine of Fuller, nearly to Roslyn, N. Y. There the low mounds of this moraine are covered and apparently crossed by the second or "inner" moraine, the Harbor Hill moraine of Fuller, a belt of frontal deposits traceable from New York Narrows along the north coast of Long Island to Fishers Island and along the south coast of Rhode Island, where, at Point Judith, the moraine, interrupted by the sea, is recognizable by soundings made southwest of Cuttyhunk, thence northeastward through the Elizabeth Islands to Woods Hole, and thence along the main arm of Cape Cod peninsula to Orleans. In the area covered by this report the second moraine is called the Falmouth moraine.

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[1] Shattuck, G. B., Pliocene and Pleistocene, Maryland Geol. Survey, pp. 66–76, 1906. The author recognized five terraces, namely, the so-called Lafayette terrace (now regarded as older than the Pleistocene), traceable at elevations above the existing wave-cut terrace of the shore between 260 and 500 feet; the Sunderland, between 100 and 220 feet; the Wicomico, 45 to 90 feet; the Talbot, 10 to 30 feet.

The terms "outer" and "inner" moraine, formerly and still sometimes applied to the Nantucket and the Falmouth moraines respectively, are not appropriate, for although they occupy these positions from the middle of Long Island eastward to the east coast, their positions west of Roslyn, on Long Island, are reversed. This change of alignment of the front may mean that in its second stage the ice sheet was thinner on the east and thicker on the west than the first Wisconsin ice sheet, a difference that may have arisen from a shift of the snow fields inward in the gathering ground. A tilt of the continent toward the southwest over New England might have had the same effect, but no evidence of such a movement has been found.

The nature of the retreat of the ice front between the first and the second substages of the Wisconsin stage is indicated in the Cape Cod region by numerous ice block holes between the Falmouth and the Nantucket moraines. The formation of these holes was accompanied by stagnation of the ice far within its front at Nantucket. Blocks of ice several yards thick appear to have remained at some places until after the glacier had readvanced into that field at the second substage. The interval between the two chief advances of the Wisconsin glacier in this region was, therefore, not long enough to permit these outlying blocks of ice to melt.

NANTUCKET MORAINE

The marginal deposits of the Wisconsin ice sheet on Nantucket consist of an outwash plain built up in front of the ice, a depression back of the head of the terrace formed by the plain, and, north of this, a belt of low hills and hollows strewn with boulders and drift. This series of deposits is here called the Nantucket moraine. The knobs and basins of this moraine, which is regarded as submarginal, differ from those of the frontal moraines in other areas, for they are composed largely of flexed and contorted beds of an older glacial series, whose eroded surface was crumpled and wrinkled by the forward-moving Wisconsin ice.

The island of Tuckernuck extends the characteristic morainal topography of Nantucket westward along the line of the ice front. The plain on the south side of the island and the corrugated moraine on its north side have been reduced by marine erosion to narrow coastal belts and the fosse in the middle of the island forms a large part of its surface.

The ice front, curving northwestward, next appears on the island of Chappaquiddick, a southeastern appendage to Marthas Vineyard, where, however, the distinctions between the plain, the fosse, and the submarginal moraine are not clearly defined.

On Marthas Vineyard the frontal features of the ice sheet reappear with typical ice contact slope along the east coast, modified by the overrunning of the ice upon its frontal outwash plain, a feature which Dr. Wigglesworth has found along the entire iceward border of the outwash plain. West of Vineyard Haven the ice either pushed through gaps in the pre-Wisconsin hills or rode over these hills, here and there depositing heaps of boulders, as in North Tisbury. The strong ridges on the western side of the island are only in small part due to the accumulation of frontal or retreatal moraine deposits. The Wisconsin drift is everywhere a thin veneer mantling older Pleistocene deposits or the Cretaceous deposits of the upland.

As the base of the ice sheet lay mainly above the level of the outwash plain, ice contact slopes are rare except at the south ends of gaps in the hills. The surface of the upland in the western part of Marthas Vineyard differs little from that of the upland many miles back of the terminal moraine except for large boulders and occasional morainal mounds of doubtful nature, and the ice front appears to have passed seaward of the western part of the island, lying south of Gay Head, as well as south of the islands west of Gay Head, nearly to Montauk Point.

From Vineyard Haven eastward to Tom Never's Head, on Nantucket, the ice front formed a lobe whose axis of maximum flowage appears to have passed southeastward, presumably along the line of the glacial striae on Cape Ann, where the stronger lines show a movement S. 10° E. From Tom Never's Head the ice front turned southeastward to form another more marked lobe over Nantucket shoals. The axis of this lobe was probably determined by the South Channel, a deep depression separating Nantucket shoals from George's Banks. From Vineyard Haven westward to Block Island a broad lobe of the ice sheet pushed out beyond the present site of the islands, probably with its axis of maximum flow along the low ground of Narragansett Bay. The topography of the insular tracts would have tended to introduce irregularities in the ice front at its maximum advance, so that the ice probably threw out small lobes in the depressions between the islands, such as that occupied by Menemsha Pond, which acted somewhat like that broader and deeper opening between Gay Head and Block Island. A curve drawn from the boulder shoal southwest of No Mans Land to Montauk, where the frontal moraine reappears, indicates that the axis may have been prolonged as much as five or ten miles south of the south coast of Block Island in the area between that island and No Mans Land.

A striking feature of the morainal topography of the outer islands is their freedom from alteration by wave action above the present sea level. Except for long-continued atmospheric weathering, which is particularly noticeable in some of the granitic boulders, the surface has been but little altered, even by fresh-water streams. A strong contrast with this retention of the forms impressed upon the surface by the glacier and the streams that flowed over the outwash plain is seen in the present destructive work of the sea in cutting away and trimming the edges of the land.

Falmouth Moraine

The second Wisconsin terminal or frontal moraine is best developed in the town of Falmouth. It skirts the shores of Buzzard's Bay and the south side of the Cape Cod Canal, where it forms a huge outwash fan of sand and minor beds of gravel, sprinkled with thousands of granitic boulders. Southwest and east of the apex of the frontal fan, which coincides in position with the interlobate angle of the ice sheet, the mounds of the frontal moraine rise above the level of the stratified drift and form rather typical morainal topography, as at Woods Hole and on the Elizabeth Islands; but farther east, along the frontal of the Cape Cod Bay lobe, the beds of outwashed sand continue to form a large part of the frontal deposits. They were more or less overrun by the ice and are pitted with large holes, which were occupied by blocks of ice left over from the Nantucket substage.

The deposits of stratified material in this moraine dwindle eastward, toward Orleans, whence the ice front appears to have turned southeastward to form a lobe whose axis, like that in the earlier Nantucket substage, lay along the South Channel. A weak interlobate axis is thus traceable from Tom Never's Head, on Nantucket, through the Orleans-Nauset section of Cape Cod, north of which the forearm of the cape lies in the interlobate axis between the South Channel or offshore lobe and the Cape Cod Bay lobe.

In the interlobate tract in the northern part of Falmouth the features of the Nantucket substage at Vineyard Haven are repeated and continued northward over the Plymouth quadrangle by the great mass of gravel and sand in the Plymouth woods, in which Manomet Hill is prominent.

A remarkable fact in the history of the three lobes in this part of the glaciated area in the second or Falmouth substage of the Wisconsin ice is the earlier melting of the ice on the west than on the east. The streams of water that built the high sand plains between ice block holes in the western part of the interlobate moraine, about Plymouth, poured southwestward from the lobe of ice lying over Cape Cod Bay, and, as Grabau[1] pointed out, the outwash plain at Eastham, on the arm of Cape Cod in that interlobate axis, was also traversed by streams running toward Cape Cod Bay, coming from ice lying east of the site of Cape Cod. It would thus appear that the Wisconsin ice sheet thinned and melted away over the present mainland before it melted over the Bay of Maine in the latitude of Cape Cod.

The moraines of this substage form the surface features of the Elizabeth Islands, but apparently not the mass of drift that stands above sea level in those islands. On Naushon and other islands large boulders are grouped in lines showing the faltering retreat of the ice front across these broad, low Pleistocene ridges. Almost everywhere in the islands a bed of yellow sand underlies the surface moraines. Conjectures as to its stratigraphic position are given in the text dealing with these islands (Pt. 3, Chap. 2). Back of the main Falmouth moraine there are numerous retreatal moraines, only a few of which lie within the area covered by this report.

Interlobate Moraines

Enormous piles of gravelly and sandy drift lie on the west shore of Cape Cod Bay, in the Plymouth woods, extending as far north as Kingston, Mass. These deposits are here called the Plymouth interlobate moraine. This moraine is a rude ridge of rather bouldery drift or till, sections of which disclose older Pleistocene deposits, including a blue clay of either Montauk or Gardiners age. Most of its sections in the interior show stratified beds of gravel. The highest mass of this moraine forms Manomet Hill, which has an elevation of more than 380 feet above sea level. A cut made in the northern part of the crest of this hill when the roads of the state were being reduced to standard grades showed a coating of gravelly till, some 12 feet thick, overlying waterlaid gravel, confirming the opinion that most of the glacial drift in this moraine is stratified. This eastern, more decidedly morainal part of the deposit is separated from the area of plains and ice block holes on the west by a line of lakes that occupy ice block holes. These lakes, which are the largest in the district here considered, include Billingston Sea, famous in the annals of the Pilgrim Fathers, one of whom is commemorated in its name. Great South Pond and Long and Halfway ponds and, farther south, Great Herring Pond, have their longer axes in the line along which the group extends, about N. 42 W. Running out southwestward from each of the larger ponds in this line, there are small depressions, the deeper parts of which are occupied by ponds or drainage lines, such as that of Agawam River, draining Halfway Pond. This complex group of sand hills, sloping plains, and ice block holes is the most singular and at the same time the most regular in its repetition of features due to the deposition of gravel and sand between and around blocks of ice that lay in these depressions, the deeper of which contain bodies of standing water.

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[1] Grabau, A. W., The sand plains of Truro, Wellfleet, and Eastham, Science, new ser., **5**, pp. 334–335, February 26, 1897. For discussion of this paper, see same volume, p. 361.

The area of a certain group of these lakes appears to have been occupied by the eastern margin of the Buzzard's Bay lobe of the ice sheet. From this margin sloping plains of outwash were laid down by streams flowing southwestward, toward Buzzard's Bay. These plains, which along their eastern margin rise to elevations of 200 and 250 feet, have the appearance of large fans built between ravines that have disappeared.

That streams flowed from the ice front at this or a later stage across the lower surfaces on the southwest is indicated by large drainage channels now occupied by small streams, such as Agawam River. Great Herring Pond drains into a channel that runs across the tract traversed by the Cape Cod Canal. The central and western parts of this channel are occupied by Manomet River, which has a course parallel to that of the smaller chains of lakes in the Plymouth quadrangle and appears to be allied to them in origin, its bed having apparently been occupied by a remnant of ice lying at the head of the Falmouth outwash fan. In this respect the depression is analogous to the fosse on Nantucket, but it is notably deeper and more complex in its relations to the neighboring glacial features. This depression appears to have been followed by streams that flowed from the Cape Cod Bay lobe or from marginal lakes in that lobate region westward into Buzzard's Bay during the retreat of the ice from the Falmouth moraine.

From the Nauset inlet northward to Pilgrim Heights, Cape Cod is composed almost entirely of plains of stratified gravel, sand, and clay, though here and there boulders are scattered on the highest surfaces in Truro or appear in certain coastal areas in beds of gravel. These plains form three rather distinct areas. The southernmost is the Eastham plain, already described as having been built by water flowing westward from an ice mass lying outside the present area of the Cape. It is the most perfect and most typical of the plains on the Cape and is among the latest glacial features there, being probably somewhat more recent than the fans and plains in the Plymouth interlobate district and on the Cape farther southwest.

North of the Eastham plain, extending through Wellfleet and Truro, there is a plain that is deeply dissected by channels locally known as "hollows," the bottoms of some of which lie below the present sea level. These hollows appear to have been similar in origin to the channel of Agawam River, in the Plymouth region. If they were occupied by remnants of the ice sheet they appear to have been modified by running water from an ice mass on the east, signs of which are found in kettles and boulders from Highland Light southward, as well as in ice block holes now occupied by lakes.

At Highland Light the blue clay of the so-called clay pounds, together with an overlying bed of fine sand and an underlying bed of coarse gravel, with an occasional erratic, reproduce in vertical section the essential features of the Jameco gravel, the Gardiners clay, and the Jacob sand in the island on the southwest and have been assumed by Fuller to be the same beds.

North and west of the Truro high plain, at about the level of the Eastham plain, there is a lower plain, which appears to have been cut back into the high plain.

The tip of the Cape at Provincetown is formed chiefly by marine deposits and sand dunes. What appears to be an extension of the glacial deposits of Cape Cod, laid down before the north end of the peninsula was cut back by the sea, was seen by Dr. Vaughan in gravel exposed at low tide on the outer beach, near Wood's End.

Cape Cod Bay is in origin analogous to the New England sounds; it is a depression back of a well-developed frontal moraine, and, like the sounds, it appears to have been scoured and deepened by the action of ice; but drainage lines like those drawn by Shaler[1] in his report on Cape Cod probably had a share in the erosion of the depression in the Vineyard interval prior to the first advance of the Wisconsin ice.

CERTAIN GLACIAL FEATURES OF THE DISTRICT

Certain features of the glacial history and the glacial deposits of Cape Cod and the New England Islands may here be considered, namely:

1. The deformation and dislocation of beds by glacial thrust
2. The correlation of the glacial deposits of New England with those of the Mississippi Valley
3. The classification of glacial deposits
4. The larger glacial erratics
5. Postglacial changes

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[1] Shaler, N. S., Geology of the Cape Cod district, Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 2, pp. 407–593 (see p. 516, fig. 86), 1898.

DEFORMATION AND DISLOCATION OF BEDS BY GLACIAL THRUST

The folding and overthrusting seen in the Cretaceous, Tertiary, and older Pleistocene beds, so well shown at Gay Head, on Marthas Vineyard, is characteristic of the beds in all the New England Islands, from Long Island to Nantucket. The equivalent beds of the coastal plain in New Jersey and farther south on the Atlantic border exhibit no such widespread distortion. Small displacements and distortion of soft beds are seen at places along the "fall line," at the contact of the beds of the coastal plain with the crystalline rocks of the Piedmont plateau, as at Richmond, Virginia, where the Miocene is faulted down against the granite. Folding is seen at some places in the coastal plain, as in the eroded anticline traversed by the Tombigbee River, in Alabama, and dislocation is found at Muscle Shoals, on the Tennessee River. None of these disturbances of the beds on the coastal plain south of the terminal moraine on Staten Island, however, have the breadth of exposure and the peculiar association with glacial deposits that are seen in the New England Islands.

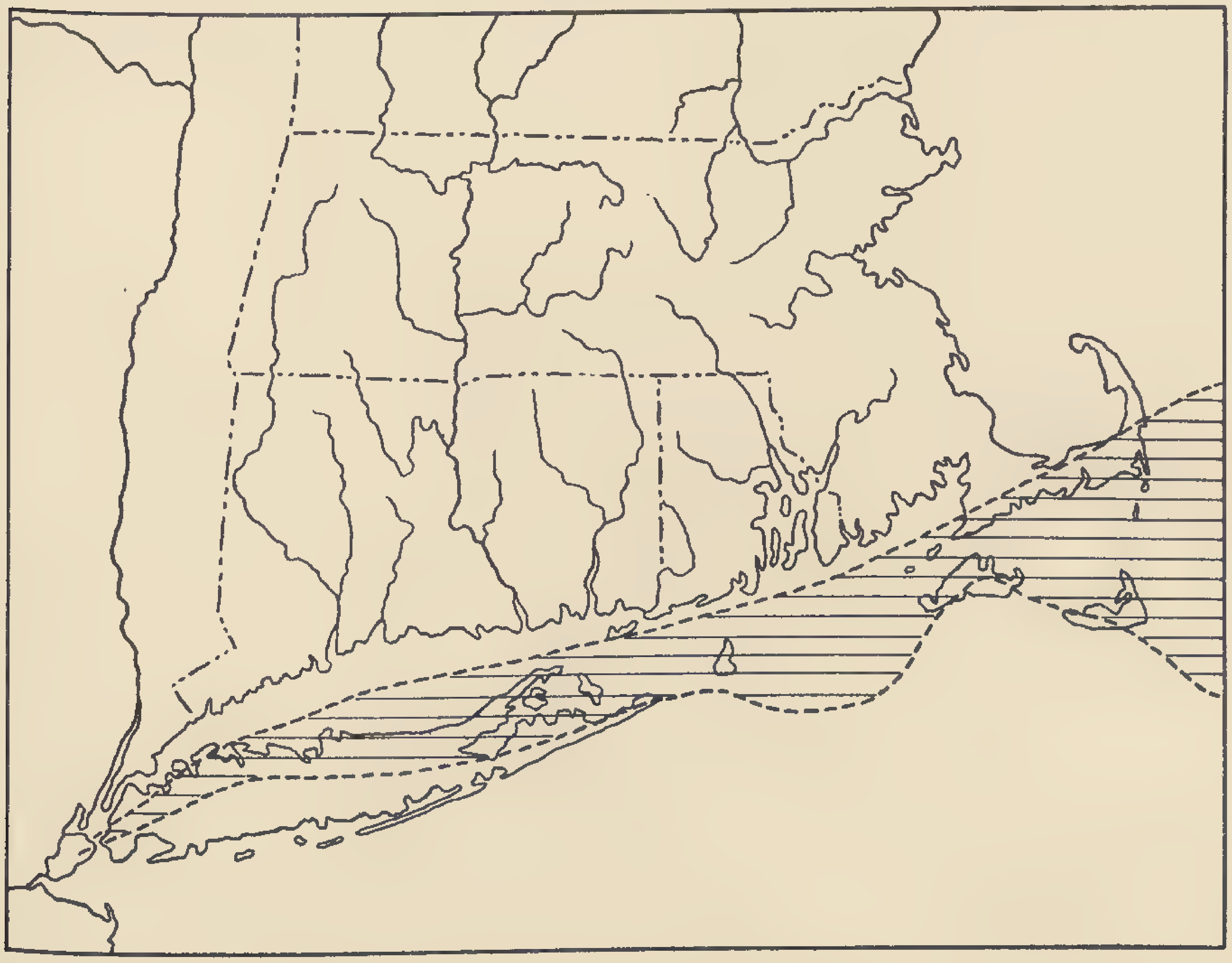

FIG. 3.— Sketch map showing approximately the area of glacial dislocation off the south coast of New England. The heavy dotted line shows the southernmost limit of the Wisconsin ice front.

The earlier explanations of the commingling of contorted drift with older soft beds, including the conception of icebergs grounding on a shallow sea floor, of violent disruption of the earth's crust, and of mountain building, have given way to the conception that an overriding ice sheet ploughed and pushed the soft beds over a coastal plain. In 1886 Merrill[1] expressed the opinion that the dislocations on Long Island were due to the advance of the Pleistocene ice sheet over the soft deposits of the coastal plain. Upham[2] somewhat later took the same view regarding the distortion of the beds at Sankaty Head, on Nantucket, and at Gay Head, on Marthas Vineyard. In 1894 Hollick[3] in considering the structure of beds studied by him on Staten Island, Long Island, and Gardiner's Island in connection with the facts reported by Shaler and others on Marthas Vineyard, compared the theory of mountain building as applied to this structure with that of glacial thrust and concluded, from the coincidence of the terminal moraine with the zone of dislocation, that glacial action alone was the cause of the folding and faulting in the beds. He also noted at Cold Springs, on the north shore of Long Island, that the lower Cretaceous beds there exposed were undisturbed, and he predicted that if excavations were made elsewhere below the limit of disturbance of the upper beds by the ice sheet similar undisturbed strata would be found.

In 1906 Veatch[4] showed by the records of well borings made along the north shore of Long Island that beneath the crumpled and dislocated Cretaceous beds that lie immediately under the glacial drift there are undisturbed basal Cretaceous beds that dip seaward.

Two facts appeared to lend support to the idea that these disturbances were due to mountain building forces, which were suggested by Shaler as the cause of the dislocations on Marthas Vineyard. One of these facts was the great extent of the area of the disturbed beds in the New England Islands. The disturbed area between New York Narrows and Sankaty Head amounts to at least 2,200 square miles, and as that area may be 20 miles wide it may have once included more than 4,000 square miles of the sea floor and the islands, exclusive of the vast shoals east of Nantucket and Cape Cod. If the disturbances were practically simultaneous throughout this great area, glacial thrust appeared to be an inadequate cause of them. Merrill seems to have held that the folding took place during the last ice stage, the Wisconsin stage. Shaler and his assistants, in their work on Marthas Vineyard, found that the disturbances at Gay Head long antedated the last or Wisconsin stage of glaciation; and Woodworth reached the same conclusion in regard to the date of the disturbance on Long Island,[1] where dislocations appear to have occurred at different times before the Wisconsin stage. The latest surveys confirm the theory of glacial thrust, showing a succession of dislocations and glacial deposits so correlated as to indicate that at each ice invasion there was more or less crowding, crumpling, folding, and disruption of the beds.

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[1] Merrill, F. J. H., On the geology of Long Island, Ann. New York Acad. Sci., **3**, pp. 258–259, 1886. Also On some dynamic effects of the ice sheet, Proc. Am. Assoc. Adv. Sci., **35**, pp. 228–229, 1886.

[2] Upham, Warren, Marine shells and fragments of shells in till near Boston, Am. Jour. Sci., **37**, ser., p. 270, 1889.

[3] Hollick, Arthur, Dislocations of certain portions of the Atlantic coastal plain strata and their probable cause, Trans. N. Y. Acad. Sci., **14**, pp. 8–20, 1894.

[4] Veatch, A. C., Underground water resources of Long Island, U. S. Geol. Survey Prof. Paper 44, pp. 16–19, 1906.

These dislocated deposits are comparable with true moraines, but they are genetically and lithologically distinct from them, for they were moved as a mass and not as detached fragments, such as boulders. The displacement of the beds appears to be the result of crumpling in a zone beneath an overthrust mass of ice that was pushed forward under competent gravitational pressure from the ice sheet. The effect of the ice thrust is wholly structural; it does not involve a change in the nature of the deposits or in their classification. The disturbed beds are therefore not to be grouped with moraines composed of rock débris that has been eroded, transported, and deposited by glaciers or by streams of water flowing within or out of glaciers. They form the "contorted drift" of English writers, the "schichtengestörung" of German geologists. They were laid down beneath a moving ice sheet; they are subglacial deposits, and their structure in the New England Islands is rather typically that of isoclines overturned in the direction of the movement of the ice, with dip toward the ice mass.

The surface of the contorted drift as it was left by the melting ice sheets is not well shown in the older greater typical masses in the New England Islands, such as those at Gay Head and Clay Head, but it is suggested by the present surface of areas covered by the last ice sheet, such as that on Block Island and No Mans Land. In these two islands the surface above sea level has not been at all changed, either by marine action or by the work of streams, and the form of the subglacial surface is there clearly shown. This surface is of the type known in the United States as "morainal," that is, it consists at some places of groups of mounds and hollows, some of them circular in horizontal section, and, at others, of long ridges or troughs, more or less sinuous in outline. This surface differs, however, from that of a true frontal or terminal moraine in that it is not primarily a product of glacial deposition, but a surface imposed upon a series of contorted and dislocated beds of diverse age and origin — the older glacial drift and the Cretaceous clay — by the overriding action of glacier ice, and here and there by the thickening of a veneer of later rubbly drift.

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[1] Woodworth, J. B., Pleistocene geology of portions of Nassau County and the Borough of Queens, N. Y. State Mus. Bull. 48, p. 632, 1901.

Within small areas the ridges and hollows of this pseudo-morainal contorted drift show a certain parallelism of direction, which is curvilinear in places, as in the so-called submarginal moraine on Nantucket. A sudden change in the direction of the axis of such a group of deposits may occur on opposite sides of a more or less arbitrary line, such as a trench or crease, as if it were due to the arrangement of ridges and gigantic puckers beneath part of the ice moving diversely toward the general front.

Owing to the lobular form of the ice front in areas of the New England Islands, the movement of the ice was not everywhere directly southward but swerved to the southwest and to the southeast on opposite versants of a lobe. For this reason, probably, the overturning on No Mans Land, on the east side of the axis of the Narragansett Bay ice lobe, was to the southeast. The opposite effects are seen on Block Island, where the ice pressed southwestward or westward, producing overthrust in those directions, with resultant troughs and ridges.

TENTATIVE CORRELATION OF THE GLACIAL DEPOSITS AND INTERGLACIAL STAGES

The correlation of the glacial deposits of New England with those of the Mississippi Valley indicated in the following table is tentative only. In the column headed ''Deposit'' the nature of certain deposits that, theoretically, should occur in the areas indicated, but that have not been found there, are placed in brackets.

There is little doubt that the terminal moraines and other later drift deposits in New England may be correlated with the deposits of the Wisconsin stage in the interior, and that the Manhasset deposits are the eastern representative of the Illinoian drift of the Mississippi Valley. The Illinoian drift is a relatively thick and widespread sheet, deposited by a Labradorean glacier long after the Kansan drift had been deeply weathered and extensively eroded. The Illinoian deposits were in turn greatly weathered and much eroded before either the Iowan or the Wisconsin stage of glaciation. The Iowan drift, although it is older than the Wisconsin, is probably considerably younger than the Illinoian. It is a relatively thin drift of less extent, deposited by the Keewatin ice sheet. It is not certainly

Correlation of the glacial deposits and interglacial stages in the Mississippi Valley with those on Cape Cod and the New England Islands

Stage		Substage	Deposit	Location and character
In Mississippi Valley	In New England			
Wisconsin (glacial)	Wisconsin (glacial)	Falmouth	[Clay] Sand Gravel Till	Offshore, under the sea? In outwash plains In outwash plains In frontal moraine
			[Gravel] [Sand] [Clay]	Laid down in advance of the ice; covered or worked over in Falmouth moraine
		Nantucket	[Clay] Sand Gravel [Till]	Offshore, under the sea? Gravel and sand in outwash plains In frontal moraine
			[Gravel] [Sand] [Clay]	Laid down in advance of the ice; covered or worked over in ground moraine
Peorian (interglacial)	Vineyard (interglacial)	Erosion		Old valleys on Marthas Vineyard and Block Island Widespread erosion on Nantucket and Cape Cod
Iowan (glacial)				
Sangamon (interglacial)				
Illinois (glacial)	Manhasset (glacial)	Hempstead	[Clay] Sand	Offshore, under the sea? Sparingly developed
			Gravel	Strongly developed
		Montauk	Till	Boulder clay
		Herod	Gravel	Well developed
Yarmouth (interglacial)	Jacob (transitional)		Sand	Well developed
	Gardiners (interglacial)	Marine invasion	Clay	Stratified glacial blue clay in the islands and possibly at Highland Light, on Cape Cod
Kansan (glacial)	Jameco (glacial)	(Unconformity) Moshup	[Sand] [Gravel] Till	Absent or in Jameco Locally in Jameco Boulder bed under clay
			Gravel Sand [Clay]	Normal facies of Jameco Local In lenses on Cape Cod Weathered and iron cemented boulder bed; supposed base of Jameco
Aftonian (interglacial)	Post-Mannetto (interglacial)	Erosion		Unconformity in Gay Head section and in Clay Head section on Block Island
	Mannetto (glacial)		[Clay] Sand Gravel Till?	Strong folding at Gay Head and Clay Head by glacial thrust; also (?) on Nantucket. Deposition of stony blue clay (till) in folds at Gay Head, overlain by gravel
Nebraskan (glacial)		Interval of glacial recession and marine invasion	Gravel Sand [Clay] Sand Gravel	The Weyquosque glacial gravel and sand are regarded as the equivalent of the Sankaty fossiliferous marine sand on Nantucket and under Cape Cod
		First glacial substage	Till	Dukes boulder bed (local)
			[Gravel] [Sand] [Clay]	Deposits laid down prior to deposition of boulder bed were removed in later changes
	Nonglacial		Cemented gravel	Aquinnah conglomerate

Basement of Cretaceous and Miocene strata.

known that the Labradorean ice sheet advanced at the Iowan stage, for Iowan drift has not been clearly identified east of the Mississippi River.

Three advances of the ice prior to the deposition of the Montauk till and the Gardiners clay appear to have occurred. One of these, indicated by the Moshup till, probably represents Kansan glaciation. The Moshup till and the Dukes boulder bed, which are exposed at but few places and have complicated structural relations, are regarded as representing two advances of the Jerseyan ice sheet, separated by an interval during which the Weyquosque gravel and sand were laid down.

The relations between the Jameco formation and the beds on which it rests are not well shown either on Block Island or Marthas Vineyard. Many of the beds at Gay Head cliffs and at Clay Head on Block Island are local or lenticular and their stratigraphic order is uncertain.

A comparison of the deposits of till in the New England Islands is hampered by differences in the state of their preservation. The deposits of the Wisconsin drift remain above sea level essentially as they were left on the retreat of the ice, except for certain weathering. Nowhere do they show modification by marine action at places above the present reach of storm waves. The great bulk of the material in the so-called frontal moraines is water-laid gravel and sand; the boulders, most of which are superficial, are only here and there huddled together along lines comparable with a frontal moraine. The average thickness of the Wisconsin till on Marthas Vineyard, Nantucket, and Block Island is probably not more than 3 feet. Over a large part of the surface the Wisconsin drift is represented only by scattered boulders, which rest in a rubbly surface layer. The thickness of the beds of water-laid gravel in the outwash plains on Nantucket is measurable approximately by their elevation above sea level. Their mean thickness in the section not yet cut away by the sea is about 25 feet. The mean thickness of the beds of gravel and sand in the plain on Marthas Vineyard is greater, though it is probably less than 50 feet, but the possible presence of pre-Wisconsin beds above sea level in that tract and the absence of borings makes any estimate uncertain.

The Manhasset series of beds of gravel and gravelly sand and the intercalated Montauk till form the thickest glacial deposit on the islands. The Montauk till, which is seen in continuous exposures in the cliffs, is probably thicker than any comparable bed of the Wisconsin till, which is an insignificant rubbly veneer, not thick enough to bury the boulders that form its grosser members. Moreover, the Montauk till is a typical boulder clay, whereas on these islands the Wisconsin till is usually an aggregate of boulders, gravel, and sand relatively free from a clay matrix. The gravel below the Montauk till (the Herod gravel member) and that above it (the Hempstead gravel member) appear to have been laid down during one glacial advance, the Manhasset.

What appears to be a boulder clay till bed at or near the base of the Gardiners clay near Nashaquitsa cliffs is in many respects like the Montauk till, but it is less than 10 feet thick. Unlike the lowest boulder beds, which are invariably water-washed deposits, this bed looks relatively fresh, as does also the Jameco gravel, which lies at nearly the same horizon or just below it. Judged by its content of blue clay and its fresh appearance, as well as its freedom from cementation by secondary alteration and deposition of salts of iron and lime, this bed of till lies above the oldest Pleistocene deposits, with whose physical aspects and wear by water it has nothing in common except its glacial origin. Its exemption from weathering and alteration is probably due to the fact that it was not exposed to leaching and oxidation above ground water or sea level so long as the Jerseyan and Kansan tills. The older beds of boulders, gravel, and drab sand, some of them containing water-worn Miocene fossils, consist of glacial material worked over by water and are comparable with the deposits now being laid down along our coast rather than with the glacial material on the land that has not been worked over by waves and currents. The distinction is as sharp and as important as that between the stratified and the unstratified drift of the last glaciation.

The lowest and oldest beds of boulders on Block Island and Marthas Vineyard contain no true boulder clay. The boulders are either embedded in stratified gravel or occur in water-washed and rudely bedded masses, having evidently been reassorted under an ice sheet by the action of waves and currents or by streams. Only at one point, in an exposure at Gay Head cliffs, have I found glacial striae on a fragment in these deposits. The appearance of these huddles of boulders and rounded gravel suggests that they were included in a sheet of morainal drift that was long exposed to the action of waves and currents on shores and shoals. In fact, the boulders are as well worn and clean as those that have been long exposed to wave action on existing shores. This characteristic has a diagnostic value in excluding from the earliest glacial origin any drift that proves to be a typical boulder clay. Any such clay is undoubtedly more recent than the Dukes boulder bed. It may lie above that horizon, in the Moshup stony blue clay below the stoneless blue clays of the Gardiners formation, or it may belong still higher up, at the Montauk horizon. No typical boulder clay of the bluish unoxidized type has been found in the Wisconsin moraines on these islands.

CLASSIFICATION OF THE GLACIAL DEPOSITS

The chief object of a classification of the moraines of Pleistocene glaciers is to assist in recognizing their mode of origin, whether through the agency of ice or water, and, by an imaginative restoration of the ice sheet or its melting remnants, to determine the position of particular deposits relative to the ice. A classification proposed by me in 1890 is here presented, expanded to include the subvarieties of moraine not specifically named in my original paper. In this classification, mode of origin is the prime factor. Deposition either within a field occupied by a glacier or just beyond its limits is a secondary factor. Position with reference to the ice, whether on its surface, within it, under it or at its side, takes a tertiary place in the classification.

Classification of glacial deposits (moraines)

Ice-laid moraine	Intraglacial moraine	Superglacial	Lateral, medial, marginal moraine of cliff débris (unstriated débris). Rock tables Ablation deposits brought up from within the ice Crevasse (vein) moraine Wind-blown sand
		Englacial	Dirt bands; crevasse (vein) moraine. Boulders; clay pockets. Drift worked in from above or up from below
		Subglacial	Ground moraine, till plains; submarginal moraines; drumlins; crag tails. Shoved blocks. Dislocated terranes; e.g., Gay Head cliffs
Extraglacial (till)	Extraglacial moraine	Ice bound; in contact with ice or once supported by it	Frontal, terminal, dump moraines at edge of ice, resting on unglaciated terrane; also lobate and interlobate moraines. Boulder belts
		Ice free; beyond and below the edge of the ice-sheet	Drop moraine on slopes. Bergdrift in seas and lakes. Boulders rolled beyond ice front
Water-laid glacial drift	Intraglacial gravel, sand and clay	Superglacial	Stream gravel and sand Some kames ? lowered to base Some eskers ?
		Englacial	Some kames and eskers doubtfully of this origin. "Englacial drift of Upham"
		Subglacial	Eskers; kames (in part); various stream gravels. Boulders (in part)
	Extraglacial gravel, sand and clay	Ice bound	Outwash plains; sand plains; esker fans; kames; pitted plains. Lateral terraces; kame terraces
		Ice free	Some sand plains; valley trains silt plains; proglacial clays. Deposits reworked by rivers, waves and currents

The ice contact is typically shown by the sloping sides of eskers (long ridges of water-laid drift), possibly by the steep sides of kames (mounds of gravel and sand), and by the edges of sand plains and deltas that were built up against the front of the ice or in open spaces within it while it was melting. The same ice contact slope is seen in the steep banks of ice block holes and of some of the larger kettle holes.

Some of the terms now used in America to designate glacial deposits are different from those used in Great Britain. In Scotland the term kame is applied to what is here called an esker. In Ireland the term esker is used for both a kame and an esker, as those terms are now used in America. Kame is here used to signify a mound in stratified drift. In New England these forms are at many places strongly developed along the iceward margin of an outwash plain in such a way as to indicate the ice contact, which is usually on the northern or iceward margin of a tract of kames. In these places the outwash material was evidently built upon wedge-shaped fronts of the ice sheet (as seen in vertical section), so that when the ice melted the material was let down to form mounds and hollows. Farther out upon the outwash plain the material was more regularly distributed, its surface sloping in the direction of the drainage, except where there were outlying remnants of ice of an earlier stage.

At some places the ridges known as eskers are subdivided so as to form a series of ridges enclosing rounded or oval hollows. The peaks and depressions in these ridges give them the aspect of inosculating kames. On such a surface the esker and the kame merge into one another and the distinction between them is lost. The term kame terrace is used for a terrace-like deposit made between the side of a valley and a tongue of ice lying in the valley. On melting out, the ice let the deposit down, in the manner of a kame, at the ice contact border of an outwash plain. Certain tracts of submarginal moraine appear to be masses of ill-assorted gravel and sand having a surface of mounds and hollows; hence the name *kame moraine*. But if *moraine* is used as it is in Europe the second part of this term is redundant, for a *kame* is a form of *moraine*. If *kame* is to be used in a generic sense, it should have prefixed to it terms denoting the special form of glacial accumulation it signifies.

The term *proglacial* has been applied mainly to beds of glacial clay laid down in bodies of water in front of an ice sheet, but it is appropriately used also to designate any deposit laid down by ice or water in front of an ice sheet. The word is correlated with superglacial, englacial, and subglacial in denoting a position in relation to the ice sheet.

There is perhaps some impropriety in grouping dislocated and overthrust beds of preglacial age with moraines. Although these beds have been moved by glacial action into their present positions they may not be detached from the terrane of which they are a part, and they thus differ from boulders and from those large shoved blocks of strata that were surrounded and underlain by glacial drift.

Most of the glacial deposits considered in this report fall into two great classes — ice-laid and water-laid drift. No drumlins or eskers are described, although certain narrow and relatively short ridges of gravel and sand that rise between two pits, kettle holes, or ice block holes in the plains and kame tracts, may be likened to eskers. These interkettle and interlake ridges are, however, quite distinct from those serpentine ridges in central and northern New England which clearly represent the aggraded courses of streams flowing toward the ice front under the ice or between walls of ice.

The classification above presented takes account only of forms produced by the action of ice and water during the glacial period. The drift deposits display depressions, unfilled areas, and eroded tracts or channels which may be classified. These fall under the following headings:

1. Depressions due to the melting out of ice
    a. In till, giving rise to pits and kettle holes
    b. In sand plains, giving rise to kettle holes and ice block holes.
2. Channels eroded by water escaping from the ice or flowing within the ice
    c. Stream channels cut in drumlins and ground moraine or across a frontal moraine
    d. Stream channels cut across an outwash plain (creases)

The numerous lakelets and ponds in the Plymouth woods and on Cape Cod are depressions formed either in the frontal moraine or in outwash plains. The outwash plains on Nantucket and Marthas Vineyard bear channels cut by streams flowing in open air from the ice front.

THE LARGER GLACIAL ERRATICS OF THE DISTRICT

Cape Cod and the adjacent islands are noted for their glacial boulders. Most of these boulders are on the uplands, in areas displaying the knob-and-basin topography of unassorted drift, commonly spoken of as morainal topography and interpreted as due to the direct deposition of material from the ice. This interpretation is sustained by the absence of boulders from the sand plains, outwash plains, or fields of water-laid drift that lay outside of the ice sheet. Here and there, as on Cape Cod and Marthas Vineyard, boulders as much as 3 feet in diameter may be seen on the plains near broken ground having a morainal topography, in places where the ice advanced upon gravel already washed out from the glacier, or where material was carried out on the plain from the ice front by glacial streams.

Boulders are particularly abundant in the morainal hills on Cape Cod from the vicinity of Orleans westward to Buzzard's Bay and thence southwestward to Woods Hole, on the iceward border of the mass of sand that forms the highest part of the land. This belt of country lies along the ice contact, where boulders dumped from the melting ice front would naturally be found. A similar line of bouldery moraine is traceable over the Elizabeth Islands.

On Nantucket and Marthas Vineyard the surface mapped as till or frontal moraine was originally much more bouldery than it is now, for many boulders have been broken up to make foundations for houses. As a result of this use of the only available supply of large blocks of stone on Nantucket, very few boulders remain there. In the settled parts of Cape Cod and of the islands the smaller boulders and blocks of rock have been gathered into stone fences; and in some areas, particularly on Block Island, the smaller stones that were not suitable for building fences have been thrown into the numerous pits that indent the surface. Notwithstanding these uses of the blocks, boulders still encumber the surface of large tracts in a way to impede or prevent the use of modern methods of cultivating the soil and reaping grain.

None of those high heaps of boulders which many existing glaciers accumulate in their frontal moraines are found in the district, or indeed anywhere along the Wisconsin frontal moraines in southern New England. The nearest approach to such a pile of boulders along the ice front is seen near the middle of Marthas Vineyard, in North Tisbury, on the south side of the northern ridge of the island, on land once owned by Professor Shaler. Certain tracts in the ice contact at the head of the Falmouth outwash plain in and about Bournedale, on the south side of the Cape Cod Canal, display a marked huddling of blocks, but no distinct pile of boulders along the ice front is seen in the Cape Cod morainal tract.

On Marthas Vineyard, No Mans Land, and Block Island, where boulder beds of older Pleistocene age crop out in the cliffs and appear to be truncated at the surface of the ground by erosion, erratics brought to the islands at different times may be commingled on the present surface. On the beaches at the bases of cliffs in which older beds of boulders lie beneath a top sheet of Wisconsin drift, it is impossible to distinguish boulders from till. It is, therefore, not possible to determine the direction of the motion of the ice by studying the boulders in connection with their parent ledges on the mainland, for these erratics may have been carried some distance forward during one advance of the ice and finally laid down after a short journey by ice moving in a different direction.

Some of the boulders in the terminal moraine on the islands and in the moraine on Cape Cod are more than 25 feet long, and one boulder measured 34 feet. The largest boulders on Marthas Vineyard and Naushon measure 29 feet. Enos Rock, in the Nauset kame fields, on Cape Cod, measures 34 feet.

Many large erratics have broken up along joint planes into a mass of smaller blocks. Here and there an erratic has been split along a single nearly central joint and the divided halves have moved apart, leaving a narrow passage between, giving rise to the name "split rock." Such split rocks are seen on the beaches within reach of the tide, where the difference in strain at the top and the bottom of the boulder may cause the fracture. Some large jointed rocks have been broken into fragments by frost and by the growth of trees. Such rocks are common on Naushon, and a big boulder described by Hitchcock in Brewster is of this sort.

Pairs of large boulders that stand in the sounds, particularly in navigable water, have been called by such names as "Rose and Crown," "Bishop and Clarks" (clerks, in modern spelling), "Hen and Chickens," all well-known danger points in Vineyard and Nantucket sounds.

POST-GLACIAL CHANGES

The postglacial changes in this district consist of slight weathering of the surface rocks, the formation of soils, the growth of swamps and marshes, insignificant erosion by small streams, notable work done by the wind in shifting sand, and the irresistible and rapid erosion of the coast by the sea. Among the effects produced by these agencies the dunes and lag gravel tracts formed by the wind and the swamps and marshes formed by the growth of plants are the most conspicuous. The soils of the district are proverbially poor, owing to the wide extent of sand in the level tracts that are suitable for agriculture. Certain areas on the upland of Marthas Vineyard and Block Island that are underlain by clay have better soils.

SWAMPS AND MARSHES

The swamps on the islands of the district are small. Most of them border or occupy small lakelets in the glacial drift, the waters of which are in different stages of displacement by the growth of water-loving plants. Hundreds of small swamps that lay in depressions on the sandy plains of Cape Cod and on Marthas Vineyard have been converted into cranberry bogs, and some depressions that contained no natural vegetation have been by means of barriers to the drainage artificially turned into similar bogs. Cranberry bogs are particularly numerous on the south side of Cape Cod between Falmouth and the east coast.

There are marine marshes on the west side of the upper arm of Cape Cod and elsewhere behind barrier beaches wherever shallow water gives opportunity for the growth of vegetation. Marshes of this type occur between Plymouth Heights and the Peaked Hill bar beach, as well as along the south shore of Cape Cod Bay, near Barnstable and Sandwich. The largest tracts of marsh are those of the Pamet River (partly converted into freshwater swamp by a dike at Truro village) and the marshes behind the beach between Nauset Harbor and the Nauset coast guard station in Eastham.

Except where they are cut back by the sea or covered by beaches of shingle the marshes are slowly increasing in area, and since 1620 have closed up several small shallow embayments, particularly where the inwash of silt by the tide has helped the growth of plants. The inner part of Wellfleet Harbor (see Plate 2) was once a small port in which vessels rode at anchor.

From point to point, along the coast, a fresh-water swamp deposit containing logs may be seen at or just below sea level, where it has been exposed by the cutting away of the drift around a kettle hole in which the swamp was formed, its original position protecting it from the intrusion of salt water. Such a deposit was exposed on the beach in front of the Nauset coast guard station in 1916. Deposits formed long ago in salt water marshes are seen at many places along the beach between high and low tide. Water-worn boulders and pebbles of such deposits are thrown ashore along the outer side of Cape Cod and fishermen report that they encounter marsh deposits on the outer bar at considerable depths below tide when they are driving the poles for their fishing gear. Masses of peat cast up by the waves are often seen on the south shore of Gay Head.[1]

WIND ACTION AND DUNES

Cape Cod and the New England Islands are often exposed to violent storms. The prevailing southwesterly wind is registered in the shape of the trees that get a foothold on the coast. Wherever the scant sod on the sandy and gravelly plains becomes broken, particularly near the edges of bluffs, where vortical movements of the air are set up, the wind sweeps away the fine sand, leaving saucer-shaped hollows strewn with lag gravel, the transported sand and dust accumulating now on one side, now on another of the hollow. In these hollows and on bare flats and the brows of gravelly cliffs, pebbles and fragments have been shaped and polished by wind-blown sand. Fantastically carved forms, combinations of water-worn and glaciated surfaces, with sand-carved facets or spoon-shaped depressions, abound along the tops of the bluffs of the Cape, along the north coast of Nantucket, and on lag gravel tracts on Marthas Vineyard. On Gay Head boulders of granite and diorite 3 feet across show sand-blasted facets.[1]

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[1] On the nature of the New England marshes see Edson S. Bastin and Charles A. Davis, Peat deposits of Maine, U. S. Geol. Survey Bull. 376.

Bluffs of gravel and sand are eroded by wind in dry weather when the sand is not held together by films of moisture. At such times the wind removes a continuous stream of sand and pebbles from the high bluffs on the ocean side of Cape Cod or on the south side of Marthas Vineyard, and high tides sweep away the sand and pebbles that reach the base of the talus along the bluff. Violent gusts carry sand over the top of the bluff to form an eolian layer near its edge. This layer gradually becomes thinner inward but may be as much as 6 feet thick at the edge of the bluff.

Of quite different type are the sand dunes along the beach. Though some are carried half a mile inland, most of them are formed immediately back of the beaches from whose sand they are fed. They reach an altitude of nearly 100 feet on the tip of Cape Cod back of Provincetown, where the most extensive tract of dunes in the district is found. Other notable dunes are seen in the southeastern part of Cape Cod, at Nauset and Monomoy; about the south shore of Cape Cod Bay off Barnstable; on the north coast of Nantucket; and east of Menemsha Inlet, on Gay Head.

The sand of these dunes consists mainly of grains of quartz but includes particles of magnetite, as well as garnet, which at some places forms thin layers between layers of grains of white quartz. These layers indicate the action of winds strong enough to blow away the light quartz but not strong enough to move heavier material. The dunes on the east coast of Block Island are darkened by grains of iron ore derived from the magnetite in the schist of the Narragansett Bay region and probably also from ilmenitic iron ore in the glacial drift derived from the stock of peridotite at Cumberland Hill, in northeastern Rhode Island, 3 miles east of Woonsocket.

On many parts of the coast the wind during dry weather blows back into the sea the sand that is thrown upon the land by gales. The difference between the trend of the beaches and the direction of the prevalent wind produces differences in the position, distribution and shape of the dune tracts. By a singular paradox, on certain beaches, such as the crescentic bathing beach on the east side of Block Island, the southwesterly dry winds move the sand northward and seaward, so that when the wind is strong the beach is lowered several inches during a single low tide; but at the same time the pebbles on the beach work up against the wind in the opposite direction to that in which the sand is traveling, for the wind scours out a small pit on the windward side of each pebble, into which it slides under the action of gravity as the sand is blown away from around it. In this manner pebbles work their way from the headlands along the wasting beach independently of the longshore motion of the surf.

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[1] For Shaler's original account of the sand-blasted pebbles on Nantucket see U. S. Geol. Survey Bull. 53, pp. 23–26, pl. x, 1889. For a statement of the sand blast theory of origin of glyptoliths see J. B. Woodworth, Post-glacial aeolian action in southern New England, Am. Jour. Sci., **47**, pp. 61–71, 1894. For notes on sand-blasted pebbles on Cape Cod see W. M. Davis, Facetted pebbles on Cape Cod, Mass., Proc. Boston Soc. Nat. Hist., **26**, pp. 166–175, pls. 1–2, 1894, including figures of pebbles from Cape Cod and Martha's Vineyard collected by Davis and Woodworth. See also E. E. Free, The movement of soil material by wind, U. S. Bureau of Soils Bull. 68, 1911.

The movement of the dunes has been troublesome at Provincetown, in the so-called "province lands," where the state of Massachusetts has made attempts to arrest the shifting of the sand by planting grasses and trees.[1] On the northeast side of Gay Head a small tract of dunes has marched inland and uphill, burying trees and shrubbery, and on the southwest side of Gay Head the dunes, sweeping inward under the prevailing southwesterly wind, have ponded the drainage.

CHANGES IN THE SHORE LINE

The most effective geological work now in progress in this district is the attack of the sea, which cuts away the land and forms beaches, bars, spits, and hooks of gravel and sand. The outer side of Cape Cod is being cut away at a rate between 5 and 8 feet a year, and the coast on the south side of Marthas Vineyard is being carried into the sea at a rate almost as fast. Nantucket is also being cut back rapidly, as at Wauwinet and in a stretch along the south coast between Tom Never's Head and the coast guard Station. Great changes have been made in a few years in the length and position of the sand bars off the embayed parts of the coast line, as at Nauset, Chatham, and Monomoy on Cape Cod, at Haulover Break, Surfside, and Smith Point on Nantucket, and south of Edgartown on Marthas Vineyard.

Within historic time several small islands near the shore have disappeared, such as Webb Island, off Chatham, and a small island north of Sandy Point, at the north end of Block Island. Beach flats formed at several places serve as a partial and temporary compensation, of little economic value, for the loss of islands and of the coast. Conspicuous among the recent deposits that form a fringe along the shore, standing but little above ordinary high tide, are the southward extension of Nauset Bar, the bars and beaches at Chatham, and the forelands at Siasconset and Surfside, on Nantucket.

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[1] Report of the Trustees of Public Reservations on the subject of the province lands, February, 1893, Appendix III, House No. 339, Second Ann. Rept. of the Trustees of Public Reservations, Boston, 1893.

On the low south coasts of Nantucket and Marthas Vineyard bars formed by the sea cut off the drowned extensions of the valleys of glacial streams, forming ponds of salt or fresh water.

As a consequence of such changes along the coast, lighthouses have been set back from time to time or new ones have been built to replace earlier structures that have fallen into the sea, as at Chatham and Nauset, on Cape Cod. Surveys showing the retreat of the coast have been made from time to time by the United States Coast and Geodetic Survey, the reports of which give the most complete account of these changes.[1]

The early charts do not afford sufficiently precise positions to warrant their free use in estimating the changes in the coast line during the three centuries in which this region has been occupied by European settlers. The earliest map of Cape Cod and the New England Islands that pretends to give much detail was apparently drawn in the second decade of the eighteenth century, probably by a Boston pilot named Southack.[2] The part of this chart that represents the coast from Block Island eastward is reproduced in Plate 7. The most that can be inferred from this chart concerns the occurrence and position of small islands and shoals. The coast line proper is sketched with very little regard to what must have been its actual alignment and position. The upright part of the arm of Cape Cod north of Nauset is represented as an island separated from the horizontal part of the arm by a crooked passage between Nauset Harbor and Cape Cod Bay. The chart bears an inscription on which is based the statement that a whale boat was taken through this passage in 1717. Captain Townshend's remarks on the historical references to this passageway across the Cape are condensed as follows:

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[1] For localities surveyed or reported, see General index of scientific papers contained in the annual reports of the United States Coast and Geodetic Survey from 1845 to 1881, inclusive; Appendix No. 6, Report for 1881, Washington, 1882. Other data will be found in the annual reports of the Massachusetts Board of Harbor Commissioners, continued as the Harbor and Land Commissioners. See Seventh Ann. Rept., January, 1873, House No. 65, for report of Henry Mitchell concerning Nauset Beach and the peninsula of Monomoy (pp. 94–108), and for report on Haulover Break, Nantucket (pp. 109–117). More elaborate recent surveys are those by H. L. Marindin, On the changes in the shore lines and anchorage areas of Cape Cod (or Provincetown Harbor) as shown by a comparison of surveys made between 1839 and 1867, and 1867 and 1890. United States Coast and Geodetic Survey, Appendix No. 8, pp. 283–286, pls. 11–12, 1891. Also cross-sections of the Shore of Cape Cod . . . between the Cape Cod and Long Point lighthouses, Appendix No. 9, pp. 289–341; both in part 2, Report for 1891. Also, by the same author, On the changes in the ocean shore lines of Nantucket Island, Massachusetts, from a comparison of surveys made in the years 1846 to 1887 and in 1891. Appendix No. 6, pp. 243–252, pls. 24–27, Rept. U. S. Coast and Geol. Survey for 1892.

[2] Townshend, C. H., Notes on an early chart of Long Island Sound and its approaches, U. S. Coast and Geodetic Survey for 1890, pp. 775–777, pl. 71.

> The chart furnishes positive proof of the existence of one of the closed passages that tradition says existed in early times through Cape Cod and sustains the statement of Capt. Bartholomew Gosnold, in 1602, that Cape Cod was then an island. That one of these passages remained open as late as 1717 is shown by a marginal note commenting on the loss of the pirate ship *Whido*.
>
> The main passage was much used in early colonial time by small vessels and boats when making voyages from the bay of Maine to Virginia. It is shown on the early Dutch and French charts and on the one sketched by Schipper Adrian Block in 1614.
>
> These memorable passages were closed up, as I have been told by Capt. William Foster of Brewster, Mass., about 150 years ago, during a furious gale of wind,[1] which was accompanied by a tidal wave. This herculean effort of the elements changed the whole east and south shore of the Cape, and deposited, in the salt marshes and lowlands, sand hills sixty feet high, and completely washed away a sand point off Nauset, where to this day, at extreme low tides, stumps of former trees have been laid bare, which have been seen by men now living who visited the spot for that purpose.

As a matter of fact this passage seems never to have been actually closed to tidal water. The ancient channel is followed by a marsh through which a modern ditch would allow high tides to course were it not for a dike about a third of a mile north of the point where the railroad crosses it. The ancient entrance on the bay side is still known as Boat Meadow Creek. As late as 1844 the sea is said to have occasionally swept through at high tide.[2]

The remarkable hollow known as Pamet River, in Truro, may at some time have been temporarily open so as to afford a passage across the Cape but probably the sea would not permit the east end of that trench to remain unbarred long by gravel and sand. It is further probable that, when the coast stood farther east, this trench was represented by one or more gullies leading down from the upland surface, in the manner of the shorter hollows on the north. Except for the beach and dune sand at the east end of this hollow the sea might now run through this passage and thus make an island of that part of the Cape which lies north of it.

Crab Bank, shown as lying east of Cape Cod on the chart of 1917, appears to have been so named because of the peculiarity of the bottom there rather than because of shallow depth. The soundings on the ancient chart show that the water gradually deepened eastward across the tract. Commander Stellwagen of the Coast Survey in 1856[3] reported that no shoal then existed at that place off the arm of Cape Cod, although it is shown on some charts.

[1] Probably a reference to the great storm of Saturday, October 20, 1770, or to that of Sunday, February 24, 1722–23; vide Sidney Perley, Historic storms of New England, Salem, pp. 41, 86, 1891.

[2] Enoch Pratt's History.

[3] U. S. Coast Survey Report for 1856, p. 115.

The chart makes "Webb Island" coincide with the long bar of Monomoy. There are other reasons for supposing that "Webb Island" lay southeast of Chatham, where the modern chart shows a small shoal with 4 fathoms of water. No trace of this shoal is seen on the map published in 1717. Indeed, it is stated in local histories that the island disappeared before 1700.

At what appears to be the south end of the Monomoy hook the map places "the Seal island sunken channel way," probably pointing to changes in that vicinity involving the disappearance of former islands of glacial drift.

The greatest changes appear to have taken place in the neighborhood of Tuckernuck and of Muskeget shoal. Four small islands are represented off the west end of Nantucket where now only Tuckernuck Island, some shifting shoals, Muskeget, and the Gravelly Islands appear above the sea. The soundings on other shoals south of Nantucket given on the map do not accord with the present soundings, which uniformly show greater depth of water. Marthas Vineyard is too grossly drawn on the map to warrant comment; but No Mans Land and the bouldery bar connecting it with Gay Head are shown with considerable accuracy. Cuttyhunk and Nashawena are represented as a single island. There is some reason for believing that in Gosnold's time the islands were tied together by barrier beaches that closed the existing Canapitsit Channel. Block Island is rudely sketched on this ancient chart. For nearly a century no better chart of the coast was brought out. What appear to be copies of this map were published in the British Coast Pilot and were used by the British navy prior to the American War of Independence.[1]

A few centuries ago the eastern coast of Cape Cod must have been very different in outline and position from what it is now, for it has been straightened out by the cutting back of headlands and the building out along shore of the winged beaches and hooks that terminate the Cape at Monomoy and Provincetown. Davis [2] has attempted to restore the old form of this part of the coast. According to his interpretation the innermost, oldest bar at Provincetown [3] may have been formed when the land on the south, between Truro and Wellfleet,

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[1] The English Pilot, the fourth book, London, 1775. Copy in Congressional Library at Washington contains (No. 8) "A map of the coast of New England from Staten Island to the Island of Breton, as it was actually surveyed by Capt. Cyprian Southack." See Phillips, A list of geographical atlases, **1**, pp. 590–591, Washington, 1909, which contains references to early maps of the New England coast in earlier editions of The English Pilot.

[2] Davis, W. M., The outline of Cape Cod, Proc. Amer. Acad. Arts and Sci., **33**, pp. 303–332, 1896. See fig. 1, p. 311.

[3] At Provincetown in 1916 Dr. T. W. Vaughan called my attention to coarse gravels on the bar at Wood End and Long Point, which indicate the former existence there of a shoal, possibly first an island, of glacial material that has been washed away.

extended seaward as much as two miles beyond the present coast. If Marindin's determination of the annual rate of recession — a mean rate of 5 feet per annum between Nauset and Highland Light — holds good for an indefinite past, the coast has retreated a mile in about 1,050 years and would have been over two miles farther east when the bars of Provincetown were begun. At the same rate of wear the narrow segment of the Cape between Orleans and Wellfleet will have been consumed by the sea within 3,000 years.

Independent calculations as to the length of time taken to change existing shore lines at several widely distant points, such as the south coast of England and the coast of Massachusetts, tend to support the idea that about 3,000 years ago certain parts of the North Atlantic shore, after undergoing a positive deleveling, were brought to their present level. Reid[1] regards the south coast of England as having been stable for about 3,500 years, or from the beginning of the Bronze Age. Johnson[2] concluded from the accordant level of the successive beach crests at Nantasket that there had been no measurable deleveling during the period of their construction, which he estimated at not less than 1,000 years, and probably 2,000 or 3,000 years. But this conclusion must meet the objections raised by those who hold that submerged peat bogs and the marshes along certain coasts are proofs that a positive deleveling is now in progress.

SUMMARY OF THE GEOLOGIC HISTORY OF THE REGION

The rocks of the neighboring mainland afford evidence of some of the conditions that existed and the events that occurred during the remote geologic past in this region and indicate the sources of the material that forms Cape Cod and the New England Islands. In late Paleozoic time the land appears to have extended far south and east of the site of the present coast. During that time gravel, sand, and clay that are now changed to conglomerate, sandstone, and shale were brought to the site of the coal beds at Mansfield, Mass., and to the adjoining part of Rhode Island. Prior to the deposition of these coal beds this ancient land had been invaded by magmas that formed granite, on the eroded surface of which the coal beds were laid down. Bordering the granite on the south, beyond the gneiss and diorite of the region about New Bedford, there were areas of Cambrian quartzite carrying marine fossils, the relics of a far earlier invasion of the sea. In Carboniferous time great quantities of these fossiliferous pebbles were carried to the region extending from Newport nearly to North Atterbury. Along with the Cambrian pebbles were a few that carried marine Devonian fossils. Pebbles of both these types were dragged out of ledges of conglomerate at Taunton and Newport during the glacial epoch and carried southward to Block Island and Marthas Vineyard.

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[1] Reid, Clement, Submerged forests, The Cambridge Manuals of Science and Literature, New York, 1913.

[2] Johnson, D. W., The form of Nantasket Beach, Jour. Geology, **18**, pp. 162–189, 1910.

While Carboniferous sediments were being laid down, bodies of granitic magma were intruded along the west side of the site of Narragansett Bay, converting sandstone and shale into gneiss and schist and forming new minerals. Abundant fragments of these rocks are found in the drift on Block Island. Farther north, about North Attleboro and near Boston, basic igneous rocks, in the form of dikes and sills, as well as lava flows, formed melaphyre, diabase, and other dark, heavy, iron-bearing rock, fragments of which occur in the drift in the region on the south. Among these igneous rocks were large quantities of an acid lava, the felsite or apo-rhyolite seen in North Attleboro and about Boston and Salem, fragments of which are found from Cape Cod and Nantucket westward to Block Island. Hot springs that accompanied this igneous action formed large masses of quartz, in stocks and in veins, as at Diamond Hill, Rhode Island, fragments of which are found in the glacial drift farther south. A few miles west of Diamond Hill there is a mass of an ancient eruptive rock, periodotite, rich in iron, fragments of which are scattered from Gay Head to Block Island.

By the end of the Carboniferous period the coal beds were thrown into mountainous folds that form what Shaler termed the East Appalachians. This mountain range probably embraced the site of Cape Cod and the neighboring islands. The height of this range above sea level at Canton Junction was probably 15,000 feet. This mass of rock, of which little or no trace here remains, appears to have been worn down nearly to the present level of the lowland of eastern Massachusetts by the end of the Cretaceous period.

During Cretaceous time weathering and erosion along the site of the present south coast of New England produced a surface of slight relief, over which streams carried sand and clay southward toward the Atlantic, which then lay at an unknown distance beyond the present islands. Thus was built up a plain like that now seen along the seaboard south of New York, on which from time to time the trees and shrubs of late Cretaceous time were buried in the low places and lagoons in which they grew, forming the lignite now found. Before the end of the Cretaceous period the sea came in upon the land, extending far inland.

Between the end of the Cretaceous period and the beginning of Miocene deposition here there was a long period of erosion, probably more than one oscillation of the land in relation to sea level. At the end of the Cretaceous period[1] the land probably rose and was somewhat eroded before any marine beds were laid down, but the possibility of transgression by the sea in Eocene time is shown by fragments of fossiliferous Eocene material found in the drift on Cape Cod. Oligocene and early Miocene time was a period of uplift.

At the time of the deposition of the greensand, regarded as an extension of the upper Miocene Chesapeake beds, to the south, the Miocene was probably a period of submergence of the lowland, in which the shore may well have lain against the upland somewhat east of Worcester, or even farther inland. The beds of greensand represent the offshore facies of deposition during this transgression of the sea. The Miocene sea teemed with life. Whales, dolphins, sharks, and probably also walruses and seals, roamed along off the shore, and crabs, mollusks, gastropods, and barnacles inhabited the bottom. The temperature of the water in this Miocene sea appears to have been not very different from that of the present sea off the south coast of New England. The only trace of land life is a single molar tooth of a primitive rhinoceros found at Gay Head.

In early Pliocene time in southeastern Massachusetts the land was uplifted and the sea withdrew. Small deposits of shell-bearing sand then laid down along the south coast have been found on Gay Head and Long Island. The fauna, so far as known, was chiefly molluscan and probably lived in shallow water along the coast. The shell beds at Sankaty Head, which are of upper Pliocene and Pleistocene age according to Dall, have heretofore been regarded as of interglacial Pleistocene age, and are so considered in this report. The upper beds of what may be called the *Macoma incongrua* zone, according to Dr. Wilson, contain species which, according to Dall, are not now living in the North Atlantic but are found in the North Pacific, indicating that a connection once existed across or around North America from Nantucket to the North Pacific Ocean. The presence of these North Pacific types of mollusks indicates a lowering of the temperature of the ocean water of 5 to 10 degrees Centigrade as compared with that of the Miocene sea in the same latitude.

The Pleistocene deposits of the New England Islands and Cape Cod consist chiefly of beds of boulders, gravel, sand, and glacial clay arranged in a more or less rhythmic series, separated by erosion between stages of glaciation. The earliest of these glacial deposits are exposed only in two areas on Marthas Vineyard and Block Island. Subsequent to what appears to be a third glacial advance, indicated by profound dislocation of the beds already laid down, the sea covered the area, spreading blue clay from Long Island to Marthas Vineyard and probably also northward along the east coast to Scituate or farther north. This was the best marked and possibly the last recorded submergence of the south coast of New England, though other lower stands of the land are suggested by the partly effaced terraces of the succeeding Manhasset and Vineyard deposits.

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[1] Stephenson, L. W., The Cretaceous-Eocene contact in the Atlantic and Gulf coastal plain, U. S. Geol. Survey Prof. Paper 90-J, pp. 155–182, with map from Long Island southward, showing Cretaceous boundary, 1915.

During the Wisconsin stage of glaciation, the last stage, two lines of frontal moraines were left in the district, one on the outer islands, including Nantucket, and the other on the Elizabeth Islands and Cape Cod. The interval between these two ice advances was relatively short, the remnants of the ice of the first not having entirely melted before the second advance. The interval between the Wisconsin glaciation and the next preceding one was much longer than the time which has elapsed since the Wisconsin ice disappeared from New England. The duration of the intervals between the other advances is not so clearly shown. The interval following the first ice advance appears to have been long enough to allow waves or streams to work over very thoroughly the glacial drift, much as it is being worked over now.

During Pleistocene time elevation and subsidence in this region appear to have alternated, the epochs of elevation corresponding to periods of glacial advance and epochs of depression to periods of deglaciation, but this generalization is not firmly established. At the time of the last ice advance the land south of Boston appears to have stood somewhat higher than it is now. The coast at Portland, Maine, has risen as much as 300 feet above sea level, and there has been no change near Lynn, Mass. A depression of 40 fathoms in the latitude of Nantucket since the Wisconsin stage would explain all the observed phenomena of submergence along the coast and account for several features on the floor of the sea.

Postglacial and recent events consist of the establishment of the existing fauna and flora on the land occupied by the Wisconsin glacier. The outer islands were occupied by animals and plants that established themselves there before the Sounds came into existence. The flora of the southern pine barrens was carried northward to the maritime provinces of Canada, which appear to have stood higher during the Wisconsin stage than they stand now.

The box tortoise, the black snake, and the mole on Marthas Vineyard, the brown snake and the mole on Nantucket, and field mice on all the outer, least accessible islands can be explained only by assuming a former connection between the islands and the mainland. Some evidence of the length of time that has elapsed since the outer islands were separated from the mainland by postglacial submergence is shown by the peculiar species of field mouse on Muskeget Island, now a mere shoal between Nantucket and Marthas Vineyard. A very similar example of variation under long isolation is seen in the mouse of Block Island. Dense forests spring up on the stagnant margin of the ice of Alaskan glaciers that approach a coast bathed by a warm oceanic current and a moist atmosphere. Such forests may have grown along the ice front of southern New England, and plants and animals may thus have bridged directly over the gaps between lands that are now separated by arms of the sea.

Long after the islands had become separated from one another and the mainland, the American Indian may have established himself in the district. Although few of his shell heaps are found on the present coasts, many of them may have been lost by the encroachment of the sea upon the land.

MINERAL RESOURCES

The valuable mineral resources of Cape Cod and the New England Islands are the Cretaceous white clay of Marthas Vineyard, the black iron sand of Block Island, and the beach cobbles that are suitable for use as paving stones. An attempt was made in 1891 to obtain capital to work the lignitic clay of Gay Head[1] but the futility of the attempt was promptly shown.

The selectmen of certain towns in the islands have from time to time sold cobblestones from the beaches to contractors for paving streets in near-by cities, but usually the inhabitants of the islands have quickly perceived the consequent danger to the shore lands, and there is now little or no commerce in these essential defenses of the coast.

The remoteness of Cape Cod rather than the absence of a grade of glacial sand suitable for use as molding sand has prevented the exploration of the region for supplies of this material. Such sand is likely to lie above the blue clay on the north shore of Cape Cod near West Barnstable and on the islands at what may be the horizon of the Jacob sand, but that formation usually lies under a cover of coarse gravel and sand which prevents the economical recovery of the finer sand.

Small beds of blue clay crop out along the shore of Pleasant Bay on Cape Cod and along the south shore of Cape Cod Bay from West Barnstable to the entrance of the Cape Cod Canal. At West Barnstable a brick kiln has been in operation for several years. The blue clay at Highland Light has been used locally. A thick section of this clay is exposed along the shore of the bay for more than a mile south of the railway station of North Truro. This and other beds of clay on Cape Cod generally occur in lenses, as they do beneath the lighthouse at Highland Light, forming the so-called ''clay pound,'' or they appear above sea level as the arches of low folds known as ''clay heads.''

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[1] Boston Herald, **90**, No. 22, Wednesday, July 22, 1891.

Small beds of clay are exposed in the western islands of the Elizabeth group and large beds of blue clay on Block Island, but the most valuable clays in the district are the white, red, and mottled clays and kaolinites of Marthas Vineyard, found on the north side of Gay Head and in the northern part of the main island from the vicinity of Menemsha pond to Makoniky, near Vineyard Haven. Several attempts have been made to ship this clay for use in making pottery and fire brick. The beds in the western part of the island are highly inclined and much dislocated, being so intricably folded in with beds of gravel and sand that it is desirable to explore the ground thoroughly with the drill before workings are started. There is a small tract at Makoniky in which the white Cretaceous kaolinite is less disturbed, and at that point an extensive plant having kilns for burning several varieties of brick has been operated. The necessity of shipping the clay by boat to the mainland is an obstacle to its successful competition with other similar clay for which all-rail transportation is available.

The beds of Cretaceous white clay at Ball's Point, Clay Head, on Block Island, and of lignitic clay farther south are too small and too much covered by Pleistocene beds to find other than occasional local use.

The beds of lignite in the Gay Head cliffs contain nodules of marcasite and acicular crystals of selenite, and the bed of greensand at the same place contains phosphatic nodules, but these materials are specimens suitable for display in a case containing natural history objects rather than useful substances; and this remark applies also to the fossil bones and sharks' teeth found at the same locality.

The bed of Miocene greensand, usually turned reddish brown where it is exposed, has been exploited mainly in the cliffs at Gay Head, east of the lighthouse. The material might be valuable as a fertilizer of the sandy soil of the island, where it occurs in sufficient quantity to be utilized, but I am not aware that any experiments have been made with it.

The water supply of Cape Cod is abundant, though most of it is underground. The same is true of Nantucket and of the eastern and southeastern part of Marthas Vineyard. In the upland part of Marthas Vineyard and on Gay

Head the underlying clay is not well stored with water, and an adequate supply for other than small household uses cannot everywhere be counted on. Wells bored and sunk in the gravel on the south side of the uplands usually give fair supplies. Similar conditions exist on Block Island, where, owing to the contortion of the beds, experience alone can determine the practicability of obtaining an adequate supply of water at any given site. In the Elizabeth Islands several successful bored wells have been put down from 150 to 200 feet or more, and for the most of this depth below sea level.

PART II

GEOLOGY OF PARTICULAR AREAS

CHAPTER I

GEOLOGY OF NANTUCKET AND ADJACENT ISLANDS

By J. B. Woodworth

NANTUCKET

GEOGRAPHY

Nantucket, which lies about 25 miles south of the main arm of Cape Cod, is the easternmost of a group of glaciated sandy and clayey islands off the south coast of Massachusetts, Rhode Island, and Connecticut. Although it is low, attaining an elevation of 100 feet above sea level at only one point, it is the third largest island in the group, and it forms a barrier behind which broad sounds afford protected passageways for ships for nearly 200 miles. On its east and southeast sides it is protected from the breakers of the heavy storms of the Atlantic by broad shoals, of which George's Banks, about 90 miles to the east, is the best known. Notwithstanding this protection the islands are encroached upon by the sea, which here and there capriciously adds piles of sand to the coast or as capriciously removes them.

Nantucket enjoys a wide reputation for its cooling sea breezes in summer and for its oceanic climate throughout the year. Its beds of glacial gravel yield an abundant supply of drinking water, and its excellent sand beaches afford varying exposures to the sea, facing the open Atlantic on its south and east sides and the quieter water of the sound on its north side. The island contains no valuable mineral resources, but the striking waste of its coast through the attack of the sea (see Plate **10**, fig. 1) and the fact that it is an instructive part of the great terminal moraine at the latest stage of the glacial ice give it peculiar geologic interest.

Nantucket appears to have been well wooded before it was occupied by Europeans, but it is now almost treeless. Evidence of the existence of the ancient forest is occasionally seen in fallen trunks of oak found in peat bogs.[1] The pines now growing on the island were set out 60 or 70 years ago, but those that were planted along the coast did not survive the attack of the high winds, and the existence of all the trees was at one time threatened by the pine moth (*Retina frustana*).[2]

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[1] Wilder, Burt G., Evidence as to the former existence of large trees on Nantucket Island, Proc. Am. Assoc. Adv. Sci., **40**, 1894.

[2] Scudder, Samuel H., The pine moth of Nantucket, Pub. Massachusetts Society for the Promotion of Agriculture, Boston, 1883.

The northeast arm of Nantucket has been at times cut off from it by storms that washed away the beach at the head of the harbor, and the island of Tuckernuck has sometimes been joined to it by storm-made beaches. Tuckernuck is virtually an extension of the so-called terminal moraine along a line running from Nantucket to Chappaquiddick, an island at the east end of Marthas Vineyard. Muskeget, which lies west of Tuckernuck, is a low, gravelly islet. South of Muskeget are the Gravelly Islands, small outlying parts of the same dry shoal

GEOLOGY

Correlation of Formations

The geology of Nantucket is shown on Plate 8. The following table shows Dall's and Woodworth's interpretations of the formations recognized on Nantucket:

Pliocene and Pleistocene Formations on Nantucket

	Arranged with lower part of Sankaty sand as Upper Pliocene (Dall's interpretation)	Arranged with Sankaty sand as equivalent of glacial Weyquosque formation on Marthas Vineyard (Woodworth's interpretation)
Pleistocene	Wisconsin glacial stage; Nantucket substage	
	Vineyard interglacial stage; erosion	
	Manhasset formation (glacial); Hempstead gravel member	
	Montauk gravelly till member	
	Jacob sand (transitional; interglacial)	
	Gardiners clay (interglacial) at Sachem spring	
	(Jameco gravel and associated deposits of till on Marthas Vineyard; not recognized above sea level)	
	Stony blue clay, passing laterally into stratified gravel and locally contorted drift of probable Manetto age	
Upper Pliocene	Upper shell bed at Sankaty Head	Fossiliferous Sankaty sand and bed of waterworn marine shells at Squam Head (at horizon of the Weyquosque formation of Marthas Vineyard)
	Lower shell bed at Sankaty Head	
	Ferruginous gravel (of Desor and Cabot), lying unconformably on light-brown sandy clay	Ferruginous gravel of Desor and Cabot (Not exposed)

The geological formations that lie deep beneath the surface of Nantucket are supposed to be extensions of the beds of Upper Cretaceous clay and sand seen on Marthas Vineyard, but such materials have not been seen above sea level or reported in well borings on the island. The sole trace of these Cretaceous deposits appears to be a drifted fragment of fossiliferous, reddish argillaceous sandstone containing poorly preserved casts of marine mollusks, the whole resembling similar drifted fragments of the Matawan formation (Upper Cretaceous) found on Marthas Vineyard. Of the Eocene and Miocene formations found elsewhere in the district, either in place or as glacial erratics, the only known trace on Nantucket consists of the battered and waterworn tooth of a Miocene shark found in fossiliferous sand at the base of the cliff at Squam Head in 1915. This deposit is a part of the Sankaty sand, which has been variously referred to the Upper Pliocene and Lower Pleistocene series. Dall held that a certain part of it should be referred to the upper part of the Pliocene series, but for reasons stated below it is here referred to the lower part of the Pleistocene series, the term Pleistocene being used to include deposits of the first ice invasion.

Pleistocene Epoch

SANKATY SAND.

The name Sankaty beds, proposed by me for the beds of fossiliferous marine sand under the Sankaty Head Lighthouse at the east end of Nantucket, is retained in this report as *Sankaty sand* to designate a group of deposits concerning which three different views have been held as to their position in the time scale and their place in the succession of local deposits. These beds appear to be the lowest that are exposed above sea level on the island. According to Desor and Cabot they rest on a bed of ferruginous gravel, which in turn overlies unconformably a bed of light-brown sandy clay of unknown thickness.

For a time J. D. Dana adopted the erroneous view that the shell-bearing beds were laid down after the glacial epoch and put them in his "Champlain epoch" of submergence. The mistake was further made of assuming that the altitude of the upper edge of a set of tilted beds indicates the height at which they had stood above the level of the sea. Upham has shown that the beds had been disturbed and that their elevation above the present sea level does not indicate their relation to the sea level at the time of their deposition. It was also shown that the deposit had certainly underlain the last ice sheet, that it was much eroded, and that it considerably antedated the last glacial stage. For many years the assemblage of fossil mollusks in the beds was regarded as evidence of their post-Pliocene or Pleistocene age. In a paper on the older Pleistocene deposits of the islands, I tentatively placed the beds at Sankaty Head at the same horizon as certain beds of sand and gravel on Marthas Vineyard, and adopted for the deposits at this horizon the name Sankaty beds, because the beds at Sankaty were fossiliferous and were well known. In Fuller's report on Long Island the Sankaty beds were described as ''separable into two distinct units, the Jacob sand and the Herod gravel member of the Manhasset formation,'' each of which had been traced by him from Long Island to Nantucket.[1]

According to Fuller the beds at Sankaty Head lie below the Montauk till and are well up in the Pleistocene series, having below them the Gardiners clay, about 40 feet thick, the Jameco glacial gravel (with possibly lateral changes to a glacial boulder clay), a lower Pleistocene glacially derived bed of gravel and sand, and finally, as the sections on Marthas Vineyard and Block Island would lead us to expect, a more or less continuous bed of washed glacial boulders at or near the base of the series.

In a doctorate thesis published by Dr. J. Howard Wilson[2] the beds at Sankaty Head are regarded as deposits laid down in a lagoon. A lower bed of shells is regarded as well protected from the sea. The upper bed of shells was laid down under colder water, supposed to be due to the readvance of the ice sheet from the north. The fossils in this bed are of more northern types than those in the lower bed. A noticeable unconformity is observed between the fossiliferous beds and overlying fine sand, which contains only minute fragments of shells and is regarded as probably wind-blown material.

Wilson made very thorough collections of the fossil shells in this bed, and found in the upper bed *Serripes laperousii* Deshayes and *Macoma incongrua* von Martens, species belonging to the fauna of the Pacific coast, not found heretofore, according to Dall, east of Point Barrow. He also found *Pandora crassidens* Conrad, a form common in the Miocene of Maryland but not known at higher horizons northeast of that district. *Pandora crassidens* and a single specimen of *Chrysodomus stonei* Pilsby were the only extinct forms discovered in the beds. Wilson regarded the fauna of both beds as Pleistocene, thinking the underlying ''clay'' of Desor and Cabot a ground moraine of this period.

In discussing the deposit carrying *Macoma incongrua*, Dall stated his inclination to ''regard that horizon as probably Upper Pliocene.'' He writes:

> I take it that the glacial period cut off the intercommunication between the two sides of the continent, but there is no reason why some of the Pliocene species should not have lingered on into the Pleistocene on the Atlantic side. But I am confident from the association of species that the period of close intercommunication was Pliocene, because the fauna shows a milder climate than subsequently. This is true all around the northern hemisphere.[3]

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[1] Fuller, M. L., Geology of Long Island, U. S. Geol. Survey Prof. Paper 82, p. 92, 1914.

[2] Wilson, J. Howard, The glacial history of Nantucket and Cape Cod, New York, the Columbia University Press, 1906.

[3] Official letter.

Dall appears to have supposed that the species considered were obtained from the lowermost bed at Sankaty, but Wilson states that they were obtained from the upper bed, which lies above the bed containing a Pleistocene fauna. These mollusks may have lived during a long and warm interglacial stage, when the conditions simulated those of late Pliocene time.

My own work at Sankaty Head has been limited to the attempt to determine the stratigraphic relations of the beds in this section to those in other sections on the island. For this purpose a few exposures on the coast immediately north of Sankaty Head were available.

In the low bluffs between Sankaty Head and Squam Head a section that was visible in the summers of 1915 and 1916 showed a tilted bed of sand containing comminuted shells, evidently the upper part of the Sankaty sand, which was unconformably overlain by a bed of till containing striated pebbles. This bed of till came out horizontally from the upper part of the bluff and was flexed downward into a vertical position, its resistance to erosion by the sea causing it to form a small buttress on the beach. In this section the Sankaty sand appears to underlie one of the beds of till in the older Pleistocene, a fact shown also, though less clearly, in the section under the lighthouse.

In the section exposed in the bluffs at Squam Head in 1915 and 1916 the same gravelly till that overlies the shell-bearing deposits on the south passed northward in nearly horizontal attitude into stratified material.

All the sections on the east coast of Nantucket exposed in these years showed that a bed of till of the type I have called a stony clay, rather than a boulder bed, lies above the fossiliferous sand. At some places this bed of till is stratified and looks like a bed of gravel containing large quantities of clay, or a bed of clay containing some pebbles (see Plate 10, fig. 2). The deposit has no feature in common with the basal Dukes boulder bed, on Marthas Vineyard, a deposit resembling the thoroughly washed huddles of boulders on a sloping beach of the present coast. On the other hand, the till strongly resembles the Moshup stony blue clay or till of the Gay Head section. I, therefore, conclude that the Sankaty shell beds lie above the base of the local Pleistocene series, defined as marking the beginning of the first ice invasion.

The time of the deposition of the shell beds and the overlying till is also suggested by a consideration of the geological structure in its relation to the time of the dislocation by ice thrust and to the Vineyard stage of erosion on the island. The front of the Wisconsin ice sheet at its farthest advance stood along the head of the outwash plain on Nantucket, covering the upland at

Sankaty Head, on which it spread a thin veneer of drift. The surface over which this ice sheet advanced was produced by the erosion of the folded bed of till and the bed of shell-bearing sand, a bed that had evidently been already deformed and folded by an ice advance antedating the deposition of the Montauk till. We are thus led to place the bed of till that overlies the Sankaty shell-bearing deposits below the horizon of the Gardiners clay and at the horizon of the Jameco formation, which has a till phase (Moshup till member) on No Mans Land and at Nashaquitsa cliffs, or to place the bed of till overlying the Sankaty sand at the horizon of the stony blue clay in the Gay Head section, which in this report is referred to the Mannetto formation, a conclusion similar to that indicated by the facts first presented. I am, therefore, inclined to place the Sankaty shell-bearing beds very low down in the Pleistocene series, above the Dukes boulder bed and under the Jameco and its Moshup till member, at the horizon of the beds of glacial sand and gravel found at the east end of Nashaquitsa cliffs (the Weyquosque formation of this report), or in like relation to the Sankaty beds of my earlier paper.

If this argument is valid, no Pliocene deposits have yet been found on Nantucket. But as the delimitation of Pliocene and Pleistocene deposits has been determined by somewhat arbitrary and very different standards and criteria it may be possible that here on the seacoast the glacial and interglacial deposits may have become interlocked with coastwise marine deposits that extend southward beyond the glacial limits and that have been regarded as parts of the Pliocene series.

FOSSIL SHELLS UNDER THE INTERIOR OF THE ISLAND

Several references to fossil shells encountered in digging wells and making excavations are found in the literature concerning Nantucket. Most of the wells in New England were dug long ago and no records were made of the beds penetrated.

In 1882 E. K. Godfrey[1] published a note by Mrs. Anne Mitchell Macy on "The botany, conchology, and geology of Nantucket," in which she states that shells like those seen in the bluffs at Sankaty Head had been found far from the bluffs. Mr. Godfrey also reproduces a letter written by Zaccheus Macy to the Massachusetts Historical Society, dated Nantucket, "ye 2d ye 10 mo., 1792," in which he says he found shells in his well at depths nearly 40 feet below the surface.

Dr. J. Howard Wilson states that in boring for a well many years ago on the

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[1] Godfrey, E. K., The island of Nantucket, Boston, 1882, pp. 32–33.

Kimball farms, southwest of the town of Nantucket, shells were encountered at a depth of 50 feet. This well affords some evidence as to the thickness of the last glacial outwash gravel deposits on the outwash plain.

The reported depths at which shells are found, presumably in the Sankaty sand, confirms the indications seen in the cliffs along the shore, that the last glacial drift of Wisconsin time, in the morainal northern half of the island and in the creased plain forming its southern half, is relatively thin.

Edward Hitchcock[1] collected a shell of *Pyrula carica* (*Busycon carica*) from a depth of 47 feet below the surface of Nantucket. The Sankaty sand and its fossil shells probably have a rather broad extent beneath the outwash plain at about the present sea level.

COARSE GRAVEL

Between the lighthouse at Sankaty Head and Siasconset there is a coarse rubbly gravel bed, from 10 to 12 feet thick at the upper part of the section, containing pebbles of Upper Cambrian quartzite, casts of *Obolella* sp., a diabase with pronounced ophitic structure, a fine-grained red sandstone resembling the red Carboniferous rock about North Attleboro, a gray conglomerate that is common in the Carboniferous coal measures of southern Massachusetts, a red-banded felsite, a dark schist resembling varieties of the metamorphosed Carboniferous rocks, hornblendic granitite of eastern Massachusetts type, diorite, fragments of reddish Cretaceous nodules and sandstone and lignitic sandstone, and some gneissic and amphibolitic rocks. Most of these rocks are of types commonly found in the drift as far west as Block Island and in southeastern Massachusetts. The felsite is the same that is found in the Pleistocene gravel from Nantucket northward, on Cape Cod, and presumably came from the Lynn-Saugus area or an eastward extension of it now beneath the sea. The bed lies unconformably on the fossiliferous sands of the Sankaty section.

SECTIONS ALONG THE NORTH SHORE

Sections along the north shore from Sherburn bluffs westward are discontinuous partly because of folds that carry the beds below sea level and partly because of accumulations of talus. An instructive section is seen at Sachem Spring, in Nantucket cliffs.

Section at Sachem Spring

	Thickness in feet
Rubbly drift and sandy soil at top	
Brown pebbly clay or till	10
Fine yellowish sand (Jacob sand)	6
Blue clay (Gardiners clay)	15

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[1] Catalogue of the collection of rocks, minerals, and fossils in the State Cabinet, Sixth Ann. Rept. State Board of Agriculture for 1858, Boston, 1859; Appendix, Agricultural Museum, p. xi, specimen No. 106.

This section shows the same succession of beds that is seen on the islands on the west, except that the Herod gravel member, below the Montauk till, is not represented. The blue clay in this section may be interpreted as the lost bed of clay at Sankaty Head, formerly seen in Anthony's Nose; the yellowish sand may be the equivalent of the fossiliferous sand, and the pebbly clay or till may be the same bed that lies above the shell beds on the east coast, but that interpretation is not made here.

In the low headland west of Copaum Pond there is a bed of pebbly clay or till carrying rounded pebbles of white quartz, probably derived from Cretaceous gravel. The base of this bed is not exposed. It is overlain by a bed of gravel, a foot thick, containing pebbles, the largest 4 inches in diameter, upon which lies a bed of fine, buff clayey sand. Upon all these beds lies the universal coastwise recent wind-blown sand, here 3 feet thick. Other exposures show what appear to be parts of the same set of beds. In the best of these sections gravelly till at the base is succeeded by grayish buff clay, which is in turn overlain by sand containing scattered pebbles.

At the southern limit of the town of Nantucket, southwest of Windmill Hill, beds of rusty clay are exposed. These beds pass southwestward under fine yellowish sand, evidently repeating the section at Sachem Spring. It is probably one of these same beds of clay that is brought up by a fold in the hill on which the water tower stands, just east of Washing Pond.

East of the town, in the Wier valley, glacial gravel is struck in shallow wells apparently at a horizon above that of the beds west of the town.

Only one bed of pre-Wisconsin till appears to be exposed on the island, and this probably lies at the horizon of the bed of stony blue clay at Gay Head, which is referred to the Mannetto stage. It nowhere carries large boulders, and at many places it passes laterally into water-laid drift. The section exposed is not as a whole exactly comparable with that on the islands to the west and lacks the apparent persistent parallelism of the beds that enabled Fuller to trace the Pleistocene above the basal beds from Long Island eastward to Marthas Vineyard. If the bed of till is at the horizon of the stony blue clay at Gay Head, the Gardiners clay proper and higher beds are not represented, probably because they have been eroded away. The island is subject to great erosion, and erosion may have taken place at one of the stages of the Vineyard interval marked by now partly masked terraces on Marthas Vineyard. The island was not only subject to erosion by the sea but was crumpled and deformed by the Wisconsin ice.

Wisconsin Stage of Glaciation

Nearly all the surface features of Nantucket, except the beaches and sand spits, are parts of the terminal moraine and the outwash deposits of the first substage of the Wisconsin glaciation. The island may be divided longitudinally into three sets of glacial features: the outwash plain, which forms its southern part and includes more than half its surface; the Nantucket moraine, which forms its northern hilly belt; and the fosse or longitudinal valley that lies between the other two areas. For most of the length of the island the northern limit of the outwash plain is fairly well shown by a bluff or ice contact slope, which marks exactly the position of the front of the ice during probably the greater part of the time it was on the island. The area north of this slope was covered with ice that extended northward as far as Labrador. The area south of the slope was free from ice, forming a plain that sloped southward to or toward the sea; and from its analogy with similar plains in front of glaciers in high latitudes today we may infer that one who might have traveled over this plain would have been impeded only by the streams of ice-cold water that flowed from the front of the ice.

THE OUTWASH PLAIN

The outwash plain that occupies the southern half of the island slopes southward except at the east end of the island, where it slopes southwestward. The crest of the ice contact slope stands somewhat more than 60 feet above sea level and the slope descends to the floor of the fosse, which lies between the 20-foot and the 40-foot contour. The crest is notched by creases that were made by streams flowing from the ice and that extend southward, over the plain. Some of the creases have received local names, such as Madequecham Valley, Barnard Valley, Wier Valley. Madequecham Valley appears to be continued across the Nantucket moraine, just west of Altar Rock Hills, to the depression at Polpis Harbor. Immediately south of the town of Nantucket the ice contact slope is scarcely distinguishable, and the deposits there include a sandy till that lies south of the general line of the head of the plain on the east.

In the western part of the island, near Hummock and Long ponds, the creases are more pronounced and the depressions are deeper, their bottoms for most of their length lying below sea level. They also extend farther north across the fosse into the region of the corrugated Nantucket moraine. The Hummock pond crease is continued in Washing and Maxey ponds and a small pond farther south, all of which appear to occupy ice block holes in a downfolded part of the moraine.

The ground about Hummock Pond, as Dr. J. Howard Wilson has pointed out, consists largely of beds older than those of the plain, clay appearing at or near the surface on the east side of the pond, where also a few boulders may be seen.

Few boulders are found on the plain. One was seen in 1915 on the line of the old railway, a mile or so from the supposed position of the ice front at the time the plain was formed. An older sheet of till may have furnished this boulder as well as those seen about Hummock Pond. On the other hand, the Wisconsin ice sheet, in its earlier substages, may have advanced beyond the site of the present island and its effects may have been largely masked by the building of the plain.

The plain must have originally extended a mile or more south of the greater part of the present southern coast line. Tom Never's Head (see Plate 11, fig. 1) is a bluff cut by the sea in the iceward part of the plain where the fosse and the ice contact slope turned southeastward along the ice front, which appears to have extended as far southeast as Nantucket shoals. The moraine probably also continued in this direction. On an ancient map of the shoals, near their southern border, is the inscription "Bow Bell is great stones," which may be interpreted as evidence of the presence there of glacial boulders.

THE FOSSE

The longitudinal valley or fosse that lies between the crest of the outwash plain and the corrugated Nantucket moraine is due to the building up of the plain south of the ice front and to the formation of the moraine north of it. It is, therefore, a depression held open by the ice that lay along the border of the ice sheet. It is evidently not a drainage channel cut by a stream that flowed from the edge of the ice during its retreat, for these drainage channels, such as that of Long Pond, stretch across the fosse and the plain alike. The bottom of the fosse, although it contains a few boulders, is the smoothest surface on the island, and it is prevailingly swampy (see Plate 11, fig. 2). Gibbs Pond, which stands within the fosse, appears to occupy a shallow depression unconnected with glacial streams. The fosse was apparently not eroded during the Wisconsin stage, and although it contains some Wisconsin drift it may represent the old surface of the island, upon which the outwash plain was built.

THE NANTUCKET MORAINE

The general position of the ice front on Nantucket is well defined by the low bluff at the northern margin of the creased outwash plain. The moraine-like mound-and-kettle surface north of this bluff, or "ice contact," is separated from the outwash plain by a depression or fosse that varies in width from half a mile to more than a mile. The mounds and kettles of the so-called morainal hills were once regarded as accumulations made inside and under the ice while the sand plain was being laid down outside of the ice, but it now appears that most of the drift in the mounds and hollows consist of stratified beds of gravel, sand, and clay laid down long before the advent of the Wisconsin ice sheet. Where the relation of form and structure can be discerned the contorted beds and the mounds and hollows conform to such an extent as to indicate that their form and structure are alike the results of deformation by the overriding Wisconsin ice sheet or by earlier ice sheets, a deformation subsequent to the formation of the surface that bevels the tilted and eroded beds of the island. The Wisconsin drift or till in the so-called morainal belt is very thin, composed only of scattered boulders and here and there a rubbly layer laid down on older stratified material. The so-called moraine is not a true moraine in the sense of a deposit made at the edge of the ice sheet.

On Nantucket the ridges and hollows of this submarginal *push moraine* or *pseudo-moraine* are typically displayed east of Nantucket Harbor, in the Shawkemo Hills, Altar Rock Hills, and Folger Hill. They are arranged in roughly parallel lines that sweep around with a somewhat curvilinear trend similar to the lobation of moraines. East of the deep crease known as Madequecham Valley, which extends south-southwest from Polpis Harbor to Madequecham Pond, the ridges trend somewhat north of west in the higher part of the area. Between Folger Hill and Sesachacha Pond the ridges and depressions trend between northwest and west of north. On the west side of Madequecham Valley the strong ridges trend northeastward, and although this trend is not shown by some ridges it reappears in strong ridges as far west as the east shore of Nantucket Harbor. Yet within this northeastward-trending group of ridges there are kettle holes whose long axes trend north of west.

The change in the direction of the lines of ridges and hollows on opposite sides of Madequecham Valley suggests that the origin of this valley is in some way associated with the origin of the hollows between the ridges, and that although that valley was occupied by a subglacial stream, as Shaler first pointed out, its position was determined by the deformation or dislocation, through ice thrust, of the underlying gravel and sand. It may be possible also that along this line there was a significant break in the nature of the deposits or in the masses of ice that pushed them forward.

HYPOTHETICAL CONSTRUCTION OF THE CORRUGATED NANTUCKET MORAINE BACK OF THE FOSSE

The evidence now available of the crumpling of the beds in the so-called submarginal moraine makes it possible to offer a better explanation than has yet been given of the mode of action of the ice sheet back of the outwash plain. If the marginal ice rested on the relatively even older Pleistocene surface, as soon as the sand and gravel washed out from the ice front had been banked up to a height that would obstruct the forward motion of the bottom part of the ice, the ice above a certain prism lying back of the head of the plain would begin to shear up. The shear plane would dip inward and downward toward the ice, cutting off a prism of stagnant ice from the live ice back of it and above it. According to this conception the topography of the head of the outwash plain and the breadth of the fosse occupied by the prism of dead ice indicate that this shear or thrust plane had an inclination from the horizontal of about 50 feet to the mile from the present head of the plain, which stands at an elevation of 60 feet. The pliable material behind this thrust plane, below the bottom of the ice, would be dragged and kneaded by the motion of the glacier. It is conceivable that successively higher slices of the ice at its front, such tongues of ice as the Mer de Glace, may have overridden the lower parts of its mass, leaving relatively inert, detached sections beneath it. This theory would explain the succession of ridges and hollows of the Nantucket moraine, especially as the alignment of the under part of the ice front could hardly have been more orderly than the mounds and hollows seen in the Shawkemo Hills.

Some evidence that the ice sheet overrode the outwash plain is afforded by beds of sandy-gravelly till, containing small striated pebbles, seen in railroad cuts southeast of the town of Nantucket. It is evident that the ice advanced over many deltas, although the ice contact slope at the head of the plain is sharp and distinctly preserved, showing the mean position of the ice front during most of the time it stood along this general line.

The gravelly or rubbly layer at the top of the cliff near Sankaty Light contains fragments of the following kinds of rocks:

Igneous rocks: A diabase with pronounced ophitic structure; hornblendic granitite; diorite. Rocks of these varieties crop out along the east coast of Massachusetts north and south of Boston.

Sedimentary rocks: Pebbles of Upper Cambrian rocks containing casts of *Obolus* sp. [*Westonia rogersi* Walcott] identical with pebbles found in the Carboniferous conglomerates of Massachusetts and Rhode Island. Fine red sandstone resembling the Carboniferous red rocks about North Attleboro, Mass. Gray compound conglomerates identical with the conglomerates in the Carboniferous areas of southeastern Massachusetts. Reddish-brown Cretaceous sandstone identical with fragments and nodules found in the drift on Marthas Vineyard, Block Island, and Long Island. Lignitiferous sandstones of Cretaceous age.

Metamorphic rocks: Gneiss and amphibolite schist; rocks like those found on the south shore of Massachusetts and Rhode Island from Newport eastward.

The fragments of Cretaceous sandstone were probably of local derivation; the other fragments may have traveled from the east coast of Massachusetts or from points now under the neighboring waters on the east.

POST-GLACIAL OR RECENT CHANGES

Since the Wisconsin ice sheet melted on Nantucket the recorded changes are few, consisting of the establishment of vegetation on the glacial gravel and sand, a slight weathering of the mainly siliceous rocks of the drift, and the results of the dominant action of the sea. Owing to the nature of the subsoil, rainfall has had little effect in sculpturing the surface, particularly as the drainage area is too small to permit the formation of rivers. The chief postglacial features are the swamps and marshes, the beaches, and the dunes along the shore. A minor feature consists of thin heaps of shells along the coast, accumulated by the aboriginal inhabitants of the island. Of some scientific interest are the sand-blasted pebbles or glyptoliths which abound in the areas of "lag gravel" on or near the brows of wind-swept cliffs, particularly along the north coast of the island.

NATURAL CHANGES

The sea is slowly wearing away the south and east coasts of Nantucket, but the points of its attack have shifted somewhat, so that places which were formerly receding are now fronted by broad sand beaches. Many years ago the cliffs at Sankaty Head and Siasconset were freed from talus by the waves, but now a broad beach encircles this part of the coast and the sea rolls in against the cliffs only in high storms. Between Siasconset and Tom Nevers Head a wide foreland of sand has been built out and, farther west, near Surfside, at a jog in the coast line, another foreland has in recent years been formed in front of the coast guard station. Between these forelands the sea has eaten away the cliffs rapidly, and at Wauwinet also it is even more rapidly changing the form of the coast line.[1] Still greater changes have modified the forms of the beach bars thrown across depressions, such as that at the head of Haulover Break, between Wauwinet and Coskata Island, and that at the west end of Nantucket.

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[1] According to Mr. W. H. Codd, the coast at Wauwinet retreated 400 feet between 1882 and October 3, 1893.

Haulover Break, so-called because whaling ships were once taken over it into the inner harbor, was surveyed in 1846 by Henry Mitchell, of the United States Coast Survey, and in 1872 by Henry L. Whiting. Between these years the main inner stretch of the beach had remained essentially unchanged; even "the lines and details of sand hills" that were not exposed to the action of the waves showed no change. Whiting[1] found, however, that between these years the shore line outside of the beach had been driven back about 100 feet. The shore line within the bay at this place had remained about as it was in 1846. Haulover Break was again surveyed by Henry L. Marindin,[2] of the Coast and Geodetic Survey, in 1890, when the outer face of the beach was 160 feet inside the line of 1874, showing a loss at the rate of 10 feet a year; but Marindin notes that the average loss since 1846 had been at the rate of 6½ feet a year. Up to 1890 there is no record that the sea breached Haulover Break, though F. P. Gulliver[3] states that he had heard of an old map which shows an opening there. According to Gulliver the sea began to break over the beach in storms somewhat before 1896, and on December 17, 1896, it broke through and maintained a shifting passage until about 1900.[4] In 1916 the ocean side of the former gap was filled by a narrow strip of beach, and on the bay side a sand spit had been built out from the south and nearly enclosed a small oval inlet.

The beach from Sankaty Head southward appears to have been built out mainly since the survey of 1846, when the apron of sand east of Tom Nevers Head extended farther out than it did at the time of Marindin's resurvey in 1890. West of the stretch between Forked Pond and Surfside the coast for a considerable distance receded about 389 feet between 1846 and 1890, entailing, according to Marindin, a loss of 165 acres of land in 44 years. This loss was still going on in 1916, when the site of the Surfside Hotel was being consumed by the waves. Miacomet Rip, at the west end of this retreating segment of the coast line, presented a concave front to the sea in 1846; in 1916 a rounded sand foreland there projected several hundred feet into the sea.

Greater changes have taken place in the position of the long beach known as Smith Point, at the extreme west end of Nantucket (Plate 9). The earliest traditions of the island indicate that this point was the landing place of Indians coming from Marthas Vineyard. Late in the eighteenth century the inhabitants of Nantucket drove their young cattle in the spring along this beach at low tide to Tuckernuck Island.[1] On a map of Massachusetts compiled "from the best authorities" by J. Denison, published sometime before 1795, a long bar is shown extending from Nantucket westward along the south side of Tuckernuck Island and to the west of it. A slight break is shown in the bar near its junction with Nantucket.[2] On another small-scale map, engraved for the New Encyclopedia by L. Low, New York, and dated 1799, the bar that now ends in Smith Point is shown extending somewhat beyond the west side of Tuckernuck to a point nearly south of what appears to be the Gravelly Islands. The bar must then have lain considerably farther south than it lay in the middle of the nineteenth century. Accurate mapping of the beach began with the survey of 1846. From that time the position of Smith Point and of the beach of which it is the west end is given by Marindin, who describes the changes it has undergone as follows.[3]

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[1] Whiting, Henry L., Massachusetts Harbor Commissioners' Seventh Annual Report, January 1873, House No. 65, pp. 109–111.

[2] Marindin, Henry L., On the changes in the ocean shore lines of Nantucket Island, Massachusetts, from a comparison of the surveys made in the years 1846 to 1887 and 1891. Plate 25 gives details of surveys of Haulover Break.

[3] Gulliver, F. P., Nantucket shore lines, Bull. Geol. Soc. America, **15**, p. 510 (footnote), 1904.

[4] Gulliver, *op. cit.*, pp. 511–513, and pl. 50. Also Ann. Rept. Chief of Engineers for 1903, p. 90.

> This point is most erratic in position. In 1846 it was situated at the end of a long and narrow sandy beach, almost directly west of the island of Tuckernuck. Ten years later, in 1856, the point was about 1 mile to the eastward, and in 1887 the point to which the name of Smiths was applied was found to the southwest of Tuckernuck Island, 3¼ miles east of its position in 1846. These remarkable changes are exhibited in illustration No. 27, which shows the position in 1846, 1856, 1887 and 1891.
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> In 1846 the south shore extended westward past the island of Tuckernuck, leaving a waterway 250 metres wide between it and the island. In 1856 this waterway remained about the same, but between 1856 and 1887 the storms wrought a great change in this locality. The beach, which was a part of Nantucket Island and which protected the south shore of Tuckernuck Island, had been beaten back on the island, filling up the water space existing in 1856. A new inlet had also broken through this beach at a point southeast from Tuckernuck, which remained open at the last survey in 1891. The survey of 1891 shows an extension of old Smiths Point beach to the westward as far as Muskeget Island since 1864, but under what condition this growth took place has not been ascertained and may not be.

Marindin found that the annual loss of land on the south coast of Nantucket for 45 years between 1846 and 1891 was 9 acres, and that the coast recedes more rapidly in the stretch toward the west than in that toward the east because of the protection given to the east end of the island by the Nantucket shoals.

Great Point, the northeastern extremity of the island of Nantucket, is a large hook formed by the cutting back of the east coast of the island and the long-shore drift of sand toward the entrance to Nantucket Sound. Professor Henry Mitchell of the United States Coast Survey has shown by a comparison of several surveys, dating from 1784, that this point had receded 1,400 feet by the time of the survey of 1874.[1]

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[1] St. John, J. Hector (Crevecoeur), Letters from an American Farmer, p. 106, Philadelphia, March 4, 1893. There is a London edition (8 vo.), 1782, and another (8 vo.), 1873.

[2] The name of the town is given on this map as Sherburne. It was changed to Nantucket in 1795. See Edward K. Godfrey, The Island of Nantucket, p. 284, Boston, 1882.

[3] Marindin, Henry L., On the changes in the ocean shore lines of Nantucket Island, U. S. Coast and Geodetic Survey Rept. for 1892, Appendix No. 6, p. 247, plate No. 27, reproduced here.

The changes on the north shore of Nantucket have been less in recent years. The sand flat built out in front of the old sea cliff known as Sherburn bluffs is fairly ancient. The lighthouse at its east end, at Brant Point, was first erected in 1746, but beacon lights were maintained there by the inhabitants as early as 1700.[2]

Before 1700 Copaum Pond, on the north coast, was a small port open to the sea, and on its shore was made the second settlement on the island. A great storm filled the entrance with sand, whereupon, in about 1720, the inhabitants moved to the present site of Nantucket. A curious relic of the ancient play of the tides in Copaum Pond may be seen in a small sandspit on its eastern shore.

Coatue Beach, whose remarkable cusps face the inner harbor, appears to occupy a position determined by Coskata Island, a small tract of glacial deposits just north by west of Haulover Break. The other beaches here mentioned derive their sand from the longshore transportation of material derived from cliffs on one or another side of them, but Coatue Beach appears to be composed, as Gulliver has suggested,[3] of sand that has been carried along the east coast of Nantucket around Great Point and then southwestward. Shaler[4] suggests that part of the sand of Coatue Beach may have been derived from the bottom of Nantucket Bay and that part of it may have been derived from Great Head. Evidence that Coatue Beach once did not exist is found in an old sea cliff on the west side of Coskata Island, where now a small lagoon is enclosed by beach sand. Before the beach at Great Point or Coatue Beach had been formed, when the sea bathed the base of Sherburne bluffs, the east coast of Nantucket, from Coskata or Wauwinet southward, must have stood farther east, and the north coast, from Coskata southwestward, must have lain west or southwest of the eastern headland. The beach at Great Point, which extends into the sound as a wing thrown off from the present eastern headlands from Squam to Sankaty, is probably working westward with the recession of the headlands upon which it depends, and it and Haulover Break are probably marching inward with the continued recession of their supporting headlands, and the breaches in the Haulover Break will doubtless be again repaired by the sea that made them in its transportation of the waste that it has wrested from the cliffs.

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[1] Mitchell, Henry, Monomoy and its shoals, Mass. Harbor and Land Commissioners' Report for the year 1886, Public Document No. 11, p. 42, Boston, 1887.

[2] Douglas-Lithgrow, R. A., Nantucket, a history, p. 279, New York and London, 1914.

[3] Gulliver, F. B., Nantucket shore line, Bull. Geol. Soc. America, **15**, pp. 521–522, 1904.

[4] Shaler, N. S., Geology of Nantucket, U. S. Geol. Survey Bull. No. 53, p. 51, 1889.

Owing to the retreat of the south coast, the ponds there that lie in the beds of glacial streams and that are held in by barrier beaches have been shortened and must continue to decrease in length. The name Forked Pond, given to the eastern member of this series of ponds, shows that within historic time it had a branch, or branches, and resembled Hummock Pond, which lies farther west. Of the Weeweeder ponds, now mere marshes, only the prongs remain. If we compare the system of creases on the south shore of Nantucket with the system on Marthas Vineyard we may infer that Nantucket has been cut back a mile or more by the sea. The convergent group of creases in Nobadeer Pond and just east of it would have had their confluence half a mile south of the present coast, and if the Nobadeer crease and the Madequecham crease became confluent they would have joined not less than a mile and a half south of the present coast. Marindin, in the paper cited above, estimates the rate of recession of this coast at 1.42 metres a year, which is equal to 1.42 kilometers (0.88 miles) in a thousand years. The southward inclination of the surface of the outwash plain would carry it below the level of the sea in the region west of Tom Nevers Head about a mile south of its present position. If the land had been stable while this cutting has been in progress this part of the island would have been cut back in 1,200 years, but the plain evidently turned southeastward at the place where Tom Nevers Head now stands, and this part of it protected the western coast from the strong southeast storms. Erosion was then probably slower, and the time consumed by it was probably more than 1,200 years.

The ponds in the channels of glacial streams indicate submergence since the streams ran across the plain, at the end of the first Wisconsin ice advance. Peat and swamp material are found submerged at several places along the coast, and are mentioned by Shaler.[1] Submerged stumps led him to believe that the island had undergone a sinking, a positive deleveling, of 2 feet since the trees grew, but this subsidence may have occurred many hundred years ago. The old beach on the west side of Coskata, as Dr. J. Howard Wilson points out, appears to have been but little depressed within the time it has taken Coatue Beach to be formed in front of it, though the beach may have sunk two feet without affording proof of a change of level. Aside from the evidence presented and considered by Shaler I am not aware of any fact that would warrant the statement that subsidence is now going on along the coast of the island.

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[1] Shaler, N. S., Geology of Nantucket, pp. 28–30.

ARTIFICIAL CHANGES

CHANGES MADE BY WHITE MEN

The geological map of the densely built-over part of the town of Nantucket is necessarily imperfect. Low, marshy ground that originally bordered the shore of the harbor has been filled, and high ground has been leveled down. The names of North and South Water Streets indicate that they were laid out along the shore, the land east of them having been gained by filling in along and beyond the ancient beach. Gull Island, the site of the brick-clay pits referred to in historical accounts, is not now an island. Everywhere glacial boulders have disappeared. Wesko, the aboriginal name of the site of Sherburn, now Nantucket, is said to mean "white stone," presumably a light-colored boulder that stood on the site. The account given by the author of "The Letters of an American Farmer,"[1] indicates that small boulders and "stones" were never so abundant on the morainal north side of the island as they still are on parts of Marthas Vineyard and on the neighboring mainland. According to the writer of these letters stones were brought from the mainland both for filling in about the wharves and for building cellar walls.

INDIAN SHELL HEAPS

Some heaps of fragments of shells left by the aborigines are found along the coast. Scant traces of these relics of the native inhabitants have been seen at several places along the east coast, at the top of the glacial drift beds and beneath a later coating of wind-blown sand. A deposit of shells covered by peat was seen in the low cliffs at Squam Head.

In 1915 layers of shells were well exposed in the low bluff on the south side of Coskata islet, at the north end of Haulover Break. The stratification in these layers indicates a change in the species gathered, if not in the local geographic conditions, while the shells were collected. The deposit begins on the east with a zone about 2 inches thick made up entirely of shells of *Venus mercenaria*. Upon this layer lie 2 to 3 inches of wind-blown sand, over which there is another thin layer of shells, chiefly of *Ostrea* sp., and a few *Venus mercenaria*, all of which is covered by old wind-blown sand and turf. A few feet west of this place a layer of *Venus mercenaria* about 6 inches thick begins the record, upon which lies a few shells of Ostrea. The whole deposit does not exceed 10 inches in thickness and is covered by later wind-blown sand. The change from the clam (*Venus mercenaria*) to the oyster (*Ostrea* sp.) is well marked in this deposit. The deposit may not be more than a very few centuries old, but even two or three hundred years ago the head of the harbor and the beach barring out the sea between Coskata and the main island must have been several hundred feet east of their present position, so that the shell heaps were laid down on the side of the present harbor rather than at its extreme eastern corner, where Haulover Break now joins Coskata islet. The erosion of the clayey till on the south side of Coskata would have made the bottom of the harbor muddy and, therefore, favorable to the growth of the clam (*Venus mercenaria*), and pebbles here and there would have afforded seats for oysters. The addition of sand from the coast on the ocean side as the head of the harbor moved westward would have in time changed the character of the bottom off the point where the shell heaps are now found, and the change from clam shells to oyster shells may mark this incident in the history of the island.

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[1] Crevecoeur, Hector St. John, The letters of an American farmer, pp. 97–98, Philadelphia, March 4, 1793.

In a small heap of shells at the top of the bluff at Squam Head, near Wauwinet, I collected shells of *Helix alternata*, a species said to be extinct on the island. The snail now living on the island (*Helix hortensis*) has been brought in by Europeans. If Binney is right in saying that *Helix alternata* is not found near the seacoast, the sea must have been much farther out when the shell heaps were made and this species was living on Marthas Vineyard and Nantucket. The land may have since been depressed in relation to the sea or erosion may have brought the seashore to its present place. Both depression and erosion may have occurred.

RELATION OF SHELL HEAPS OR KITCHEN MIDDENS TO DUNES AND BLOWN-SAND TRACTS

All the small patches of Indian shell heaps or kitchen middens found in the bluff along the coast crop out beneath layers of fine wind-blown sand. Thus it appears that the coastal strip of wind-blown sand that surmounts the bluffs on the eastern and northern sides of the island is more recent than the shell heaps. This natural relation is a result of the retreat of the bluff and the blowing up of fine sand to its top and a few yards inland. The occurrence of kitchen middens beneath a layer of sand at the present coast line probably means that the site of the shell heaps was not far from salt water and that the retreat of the bluffs has not exceeded a few hundred feet. At some places, however, it may have amounted to as much as half a mile, if the position of certain shell heaps on Marthas Vineyard and Chappaquiddick Island are significant.

SAND-CARVED PEBBLES OR GLYPTOLITHS

At many places on Nantucket, particularly near the tops of the wind-swept gravelly bluffs that face the harbor and at places west of Sherburn bluffs where glacial pebbles and larger stones are exposed to a natural sand blast, hundreds of pebbles and stones show faceted surfaces, some of which have intersecting planes, forming so-called edged pebbles, or glyptoliths. Most of these pebbles and stones display a high polish. The under sides of many of them have water-worn or glaciated surfaces; the under sides of others are polished, proving that they have been turned over since they were first exposed to the natural sand blast. Some of these sand-polished pebbles are shown in Plate **12**. These pebbles were found in the course of a survey on bluffs where the wind was blowing up sand and where sand carving is actively in progress. Figures showing some of these sand-blasted pebbles are given in Shaler's report on the geology of Nantucket, where however, their polish is ascribed to the action of glacial streams. The present accepted explanation of the polish on these pebbles, which occur at many places in glaciated regions of North America and Europe, was advanced by Mickwitz as early as 1876, but it did not find acceptance in this country until after Shaler's report had been published.

TUCKERNUCK ISLAND

The geology of Tuckernuck Island duplicates in general that of Nantucket. The northern part of the island is a remnant of the corrugated moraine of northern Nantucket. A slight longitudinal valley that extends between East Pond and North Pond separates the moraine from a tract of outwash plain on the south, which forms the greater part of the area of the island. The fosse and the ice contact slope at the head of the plain show that the ice front extended north of west across the island to Chappaquiddick Island and Marthas Vineyard, where similar features occur.

MUSKEGET ISLAND

Northwest of Tuckernuck Island, at the present west end of the group of islands and shoals of which Nantucket is the largest mass of land, there is a low, wind-swept island known as Muskeget. On a map made at the beginning of the eighteenth century and accredited to Captain Southack the name ''Sturgeon I.'' (island) is attached to an island west of what appears to represent Tuckernuck. North of this island, on the south margin of a shoal having soundings of 3 feet, the map has the name Muskeget Sand. This map confirms the geological probability that Muskeget was once larger than it is now and that it was morainal land analogous to Saul's Hills on Nantucket and resembled the part of Nantucket that lies along the line of the outer Wisconsin moraine, which stretched lobewise from the east side of Marthas Vineyard southeastward over the site of Muskeget and Tuckernuck Islands to and beyond Nantucket.

The geological mapping of Muskeget began with C. H. Hitchcock's map in the Massachusetts Atlas of 1871, where the islet is colored to indicate the presence of "Drift and alluvium." In the map in Shaler's report on the geology of Nantucket,[1] Muskeget is shown as a postglacial deposit but is not mentioned in the text. Dr. Gerrit S. Miller, who visited Muskeget in 1892 and 1893, writes:

> Muskeget is about two miles long and at the widest part about half a mile across. It is broadest at the east end, but toward the west it tapers gradually and irregularly, at the same time bending into an imperfect and shallow crescent, the convexity of which is directed north, toward Nantucket Sound. The southwestern end of the island extends as a slender tongue of sand called South Point and is separated from Smith's Beach by a narrow channel. South Point is exposed to the full force of the tide and waves, and as a result is constantly changing in form. . . . The island is, as Mr. Allen describes it, low and sandy — in fact, a mere dry sand bar, nowhere rising more than fifteen feet above highwater mark. The surface is irregularly ridged and furrowed, the general trend of the furrows being nearly east and west, or parallel to the main axis of the island. Some of the deeper hollows contain small freshwater ponds or marshes, and there is a salt marsh at the margin of the cove on the south side, but the island is elsewhere perfectly dry and covered with coarse shifting sand. In spite of its barrenness Muskeget has a varied flora, embracing most of the sand-loving plants found on the coast of southern New England.[2]

Muskeget appears to be a wave-leveled remnant of the terminal moraine. Its antiquity and its long separation from the neighboring islands is indicated by its beach mouse (*Microtus breweri* Baird), an account of which is given by Miller. This species, which is closely related to a field mouse that is widely distributed on the mainland of New England, appears to have varied from the parent type during its isolation on this island.

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[1] The geology of Nantucket, U. S. Geol. Survey, Bull. No. 53, 1889.

[2] Miller, Gerrit S., The beach mouse of Muskeget Island, Proc. Boston Soc. Nat. Hist., **27**, pp. 76–77.

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CHAPTER II

GEOLOGY OF MARTHAS VINEYARD

By Edward Wigglesworth

GEOGRAPHY

General Features

Marthas Vineyard is the second largest of the so-called New England Islands, being exceeded in size only by Long Island. It is roughly triangular in shape, with the apex of the triangle to the north, and its southern shore line is remarkably straight. Its greatest length from east to west is 20 miles; its length from north to south is about 9 miles; and its total area is about 96 square miles. Chappaquiddick, at the east corner of the triangle, has been from time to time cut off as an island. Gay Head, at the west corner, has probably long been a part of the main island, with which it is connected by a more permanent beach, behind which a small marsh has been formed.

Marthas Vineyard is separated from the ''heel'' of Cape Cod and from the Elizabeth Islands by Vineyard Sound, which ranges in width from about 3 miles at the apex of the triangle to more than 5 miles at its west corner. The shore of the island along Vineyard Sound consists of a series of headlands and intervening lower stretches, which form irregular curves. Most of the headlands are steep cliffs, some of which are more than 100 feet high. The shore between the cliffs is at some places only a low bank or a rather flat beach. Freshly cut parts of the cliffs show that the coast facing the sound is being pushed back.

The eastward continuation of Vineyard Sound is known as Nantucket Sound. The shore along this sound is a low beach except near the apex of the island and on Chappaquiddick. Near the apex, between East Chop and Oak Bluffs, there is a long bluff about 40 feet high, and on Chappaquiddick there are similar bluffs at the entrance to Cape Poge Bay and the end of Cape Poge. Sengekontacket Pond and Cape Poge Bay are lagoons formed by bars thrown up by the waves of Nantucket Sound. Thus, although the headlands at East Chop and Cape Poge are being cut back, the remainder of the shore has been built forward by the formation of barrier beaches.

Marthas Vineyard is separated from Muskeget and Nantucket, which lie more than 5 miles to the east, by Muskeget Channel. The east shore of Chappaquiddick consists entirely of a barrier beach, which is tied at its north end to

Cape Poge and at its south end to Wasque Point. Behind this beach lies a long lagoon. The front of this beach is very straight and runs nearly due north and south.

Topographic Divisions

Marthas Vineyard may be divided into three topographic areas, as follows:

1. An area of hilly country, which occupies the western part of the island and extends northward almost to its apex.
2. A northeastern area, which lies between West Chop and Chappaquiddick.
3. A great plain, which occupies the south-central part of the island.

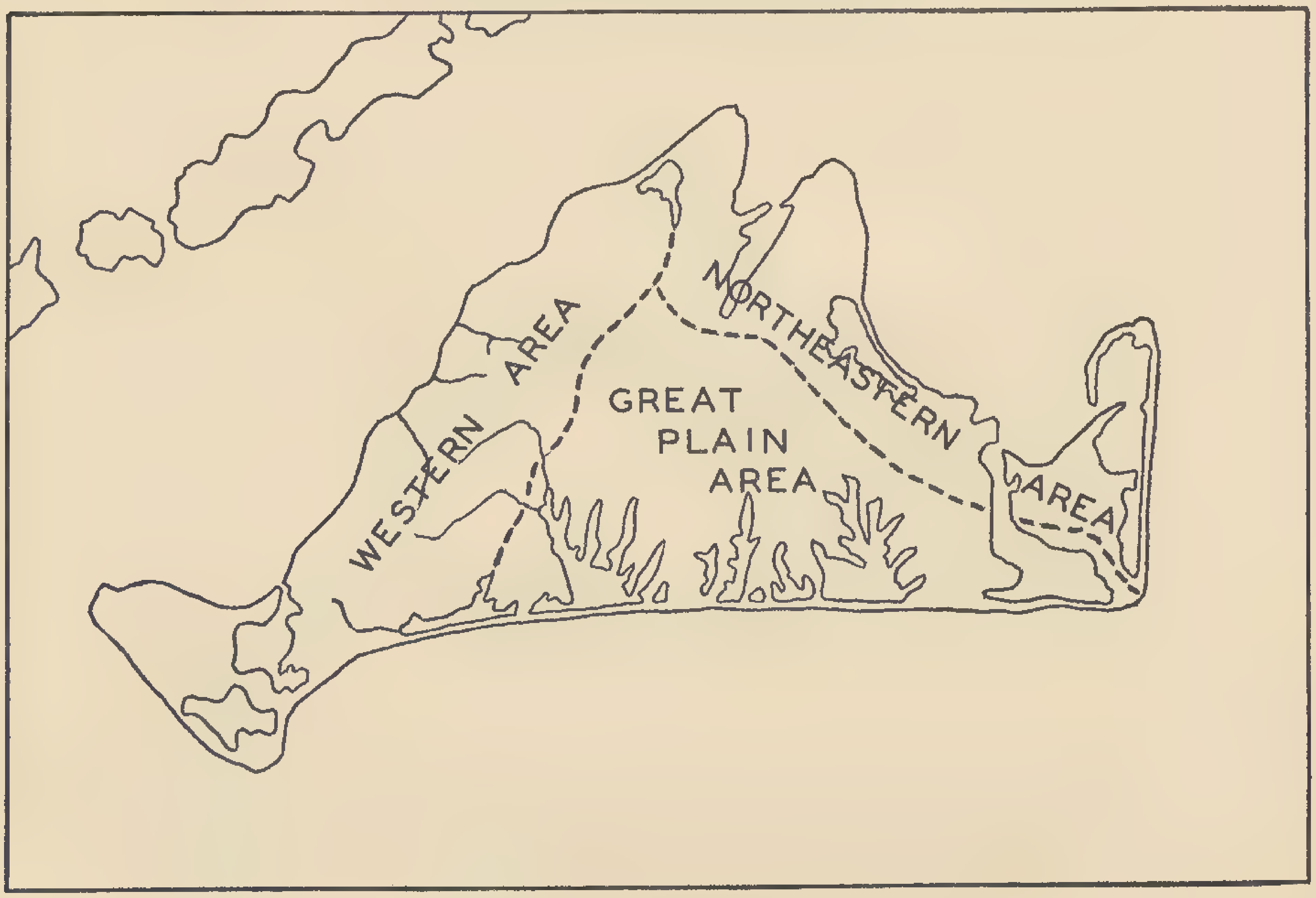

Fig. 4.— Outline map of Marthas Vineyard showing the three topographic areas.

THE WESTERN AREA

The western area has by far the most varied and rugged surface found on the island, consisting largely of boulder-strewn ridges that run roughly parallel to the shore (Plate 15, fig. 1, and Plate 16, fig. 1). Topography of this type extends from the east side of Chappaquonsett Pond southwestward to Gay Head and the southwest shore, along which there are steep cliffs. Gay Head is justly famous for its striking array of beds of bright-colored clay. (See Plate 14). The ridges in this western area attain elevations of 300 feet. They are not continuous throughout the area but are interrupted by small valleys and near the southwest end of the island by two large ponds, which stand at sea level and nearly separate the township of Gay Head from the rest of the island. In addition to these large ponds there are a few small ponds at higher levels. The materials composing the other two areas of the island are too porous to hold water on the surface, and this western area is therefore the only one of the three that has a drainage system sufficiently well developed to form brooks.

THE NORTHEASTERN AREA

The northeastern area includes the north-central part of the island, a strip along its northeast shore, and the greater part of Chappaquiddick Island. This area is widest at its west end, where it includes the apex of the triangle that forms Marthas Vineyard. It measures nearly 4 miles from north to south. Midway between its extreme ends it is not more than half a mile wide. Its surface is much less rugged than that of the western area and closely resembles that of the north half of Nantucket. It includes no distinct ridges, and most of it stands not more than 120 feet above sea level. This area is not continuous but is interrupted by Vineyard Haven Harbor and Lagoon Pond, as well as by Edgartown Harbor and Katama Bay, which cut off Chappaquiddick Island from the rest of Marthas Vineyard.

THE GREAT PLAIN

A great plain makes up the remainder of the island. To the eye this appears to be a great level stretch interrupted only by the remarkable channels in whose southern parts lie the large ponds that are so conspicuous on the topographic map. At its north edge this plain has an elevation of 100 feet, from which it slopes southward at the rate of 20 feet to the mile until it reaches sea level. Most of it is barren and uninhabited and is covered with scrub oaks. (Plate 15, fig. 2).

Notable Topographic Features

Ponds and bays are notable features of the topography. A deep reëntrant is formed at the apex of the triangle by Vineyard Haven Harbor and Lagoon Pond, which are now nearly separated by a narrow barrier beach, but which once formed a continuous body of water that extended nearly 4 miles inland.

This reëntrant is probably a submerged valley formed before the last advance of the ice. Two ponds of the same origin, though smaller, are Chappaquonsett and James Ponds. Menemsha Pond, near the southwest corner of the triangle, nearly separates Gay Head from the main island, and just south of Menemsha Pond, beyond that part of the island known as Nashaquitsa, lies Squibnocket Pond. The depressions in which these ponds lie are probably not due to absence of Wisconsin morainal material but to depressions in the surface on which the moraine was deposited. Both ponds would be large, open bays except for barrier beaches, which entirely shut off Squibnocket Pond and would probably shut off Menemsha Pond had not large jetties been built to keep the entrance open. The larger bodies of water on the south shore include Chilmark Pond, Tisbury Great Pond, Oyster Pond, Edgartown Great Pond, and Katama Bay. All these bodies are in the great plain and all have characteristic shapes due to the forms of the channelways in which they lie. With the exception of Katama Bay all have long, narrow arms or branches called coves. On the northeast shore the prominent bodies of water are Cape Poge Bay and Sengekontacket Pond. These also owe their existence to barrier beaches.

If we attempt to restore the shore line of Marthas Vineyard before these bays and ponds were formed by barrier beaches, we shall be struck at once by the extreme irregularity of the island, in contrast with its present fairly simple outline, yet such an irregular shore line must have existed at some earlier stage.

Geologic Significance of the Topography

There is a close relation between the form of the surface and the geologic structure on Marthas Vineyard, but apart from the geologic sections exposed in some of the cliffs there are few places on the island where anything but the surface of the uppermost formation can be seen. At most places, therefore, the nature of underlying beds must be inferred from the topography. The inferences thus made will generally be trustworthy if two facts are borne in mind, namely (1) that in the western area all pre-Wisconsin beds were pushed or dragged up by the ice and form the foundation on which the true Wisconsin morainal ridges rest; (2) that the Wisconsin deposits were laid down on a surface that had reached maturity. Thus the morainal material does not consist entirely of Wisconsin gravel, and not all the valleys can be attributed to the action of the last ice advance and subsequent causes. The topographic evidence is locally of still further value, for the nature and even the structure of the material at some places furnishes no aid in the task of discriminating between one deposit and another. The division of the island into the three areas here discriminated is chiefly topographic, but each division is composed of essentially different geologic deposits.

Salient Geologic Features

Marthas Vineyard presents a wider range of geologic formations than any one of the other islands considered in this report, or than Cape Cod, and is of special geologic interest for three reasons: (1) It is underlain by Cretaceous and Tertiary beds like those found on the Atlantic coastal plain, which are exposed at several places and are not found farther north or east; (2) it is the only one of these islands on which the Tertiary beds seen on the coast plain are manifestly in contact with the overlying Pleistocene deposits; and (3) the Pleistocene series is more nearly complete here than at any other place in New England and is comparable with the series found on Long Island (see Plate 13.)

Marthas Vineyard is probably underlain everywhere by Upper Cretaceous beds, but they are exposed only in the western half of the island. Upon these beds, here and there, patches of Tertiary deposits are found. In the eastern half of the island the deposits of both systems lie below sea level. Both the Cretaceous and the Tertiary beds have been greatly deformed by the advances of the ice sheets of the early part of the Pleistocene epoch, and the beds of both systems are unconsolidated, consisting largely of clay, sand, and gravel. Unconformably upon the Tertiary beds lie a remarkable series of Pleistocene deposits, which are similar to those of Long Island. The lowest Pleistocene beds consist of a basal conglomerate overlain by gravel and bouldery till and are only obscurely exposed, but wherever seen they are distorted, along with the Cretaceous and Tertiary beds, and they have obviously undergone long erosion since their deposition. Upon these oldest Pleistocene beds lies a thick dark clay, which grades upward into a fine sand. These beds are at the geologic horizon of the Gardiners clay and the Jacob sand on Long Island and are much less disturbed than the older beds, but they show considerable deformation. Upon these lies a series of beds of sand and gravel separated by a thick bed of till. This series corresponds exactly to the Manhasset formation on Long Island, and its deposition, like that of the Manhasset, was followed by a long period of erosion before it was covered with the Wisconsin glacial deposits. The Wisconsin deposits were therefore laid down on a maturely dissected land surface and they attain considerable thickness at only a few localities outside of the great plain. At many places they are only 2 or 3 feet thick.

EFFECTS OF THE WISCONSIN ICE SHEET

The present form of Marthas Vineyard is due primarily to the action of glaciers and glacial streams, and only secondarily to the later work of currents, waves, and winds. Stream erosion since the retreat of the Wisconsin ice sheet in this region has played only a small part in the development of the topography. Stream erosion before the advent of this ice strongly influenced the form and distribution of the Wisconsin deposits.

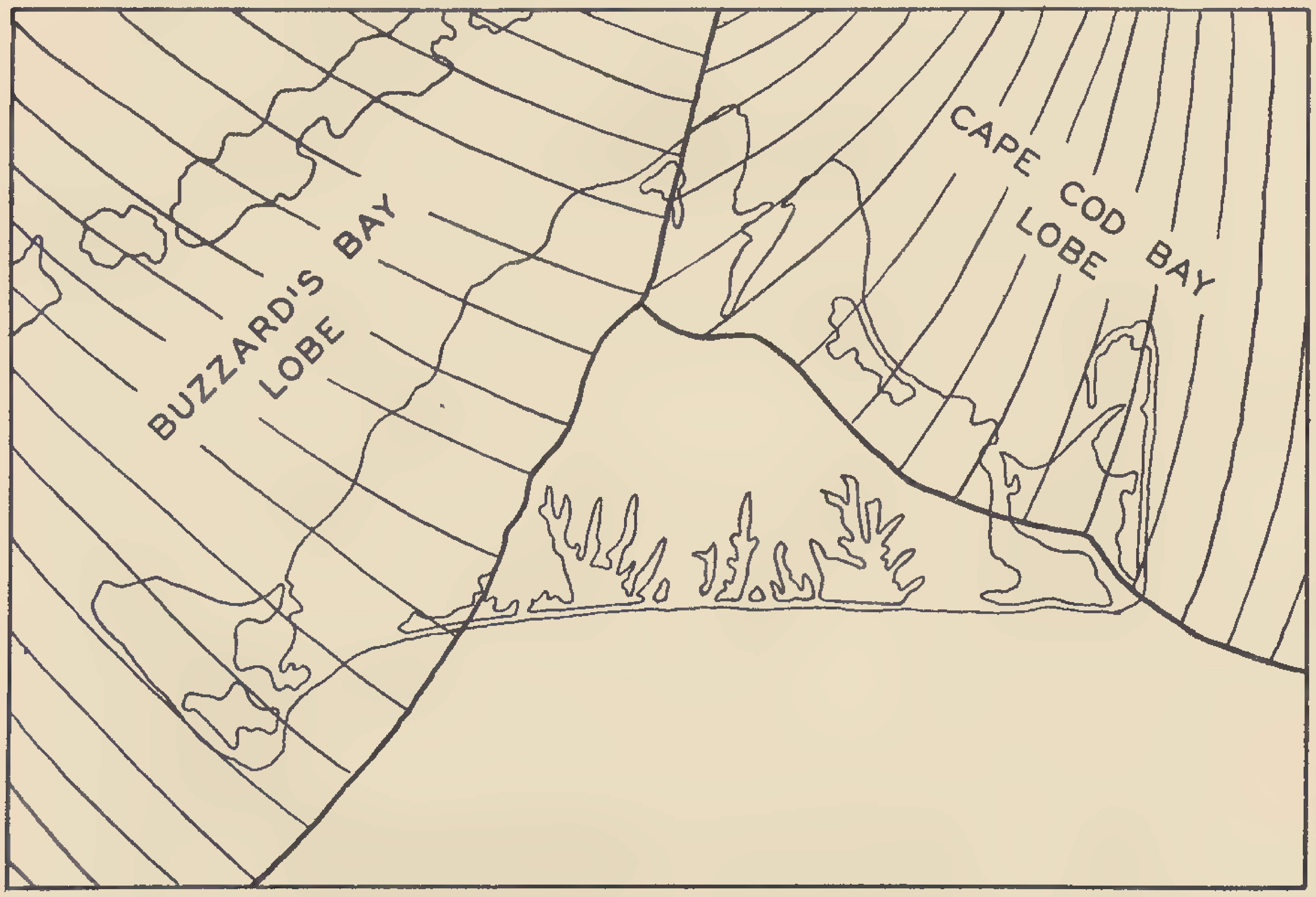

FIG. 5.— Map showing position of the lobes of the Wisconsin ice sheet on Marthas Vineyard at the time of the farthest advance of the ice.

Marthas Vineyard is a typical interlobate part of the terminal moraine and represents the southern limit of the action of the Wisconsin ice in this region. The ice covered at one time the two northern areas of the island but did not extend to the great outwash plain, except perhaps temporarily to its northern border. The presence of the ice in one part of the island and not in another caused the difference in the topography of these parts. The advancing ice found here no hard rock, but only the Cretaceous and later beds of clay, sand, and gravel. It might, therefore, be expected that the ice would have completely destroyed all the preëxisting topography, but it seems rather to have passed gently over the surface without materially altering it, except that it deposited a relatively small quantity of material in characteristic forms. (Plate **16**, figs. 1 and 2). Hence the topography is in two ways exceptional: because the ice passed over only soft rocks and because its action was weak, whereas in other parts of New England it seems to have been strong.

The southern margin of the Wisconsin ice sheet was made up of a series of lobes.[1] Only two of these lobes will be considered here. What may be called the Buzzards Bay lobe extended over the site of Buzzards Bay reaching as far south as the northwestern part of Marthas Vineyard. Its margin extended from near Vineyard Haven southwestward nearly parallel to the shore and thence to No Mans Land. The Cape Cod Bay lobe covered the site of Cape Cod and what is now Nantucket Sound and reached the northeast shore of Marthas Vineyard. Its margin extended from near Vineyard Haven, where it was in contact with the Buzzards Bay lobe, southeastward toward Edgartown, across Chappaquiddick to Tuckernuck and Nantucket.

North of the point where the margins of these lobes met there must have been an interlobate line of slack ice. Along this line was deposited an interlobate moraine (in this report called the Plymouth interlobate moraine), which is weakly developed between Vineyard Haven and West Chop and was strongly developed from Falmouth to Plymouth[2] at a later stage.

FORM OF THE ISLAND

During the first stage of the Wisconsin ice Marthas Vineyard occupied an interlobate area between the Buzzards Bay lobe and the Cape Cod Bay lobe. Its position at that time mainly determined its triangular form, which was developed in a reëntrant angle between these two lobes. The western and northeastern areas, however, were intraglacial, but the great plain was distinctly extraglacial. The topography of the western area is due to the action of the Buzzards Bay lobe on the preëxisting topography. The topography of the northeastern area is due to the action of the Cape Cod Bay lobe. The great plain was formed between these two lobes by the water that flowed from the melting ice, largely that coming from the Cape Cod Bay lobe.

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[1] Chamberlin, T. C., Preliminary paper on the terminal moraine of the second glacial epoch, Third Ann. Rept. U. S. Geol. Survey, pp. 291–402, 1883.

[2] Upham, Warren, Terminal moraines of the North American ice sheet, Am. Jour. Sci., 3d ser., **18**, p. 204, 1879. (This paper contains the first reference to this interlobate moraine.)

INFLUENCE OF THE OLDER TOPOGRAPHY

The attitude and the elevation of the older beds determined to a considerable extent the type of topography that was developed on them by normal stream action during the interglacial period preceding the advance of the Wisconsin ice. The surface of the low-lying plain and of the northeastern area, in both of which the beds are but little or not at all disturbed, was not much altered by the erosion, but the western area was considerably altered, for it stood high enough to allow the streams to cut rather deeply and the structure of its beds controlled to some extent the courses of the streams.

THE BUZZARDS BAY LOBE

The topography of the western area must be ascribed mainly to the action of the Buzzards Bay lobe of the Wisconsin ice sheet. On reaching Marthas Vineyard the ice encountered rather high elevations formed by deposits laid down by earlier glaciers on beds of clay and sand. On these beds the ice deposited morainal ridges of gravel and a thin coating of till. The ice moved forward long and in great volume, covering the high elevations and passing down on to the plain, but it probably did not reach the limit of its advance until near the end of this substage of the Wisconsin ice sheet. In the meantime it melted almost rapidly enough to counteract its forward motion, and an immense quantity of sand and gravel was washed out beyond its edge. As the ice melted, it deposited as a sheet of till the part of its load that was not thus washed out, and this till

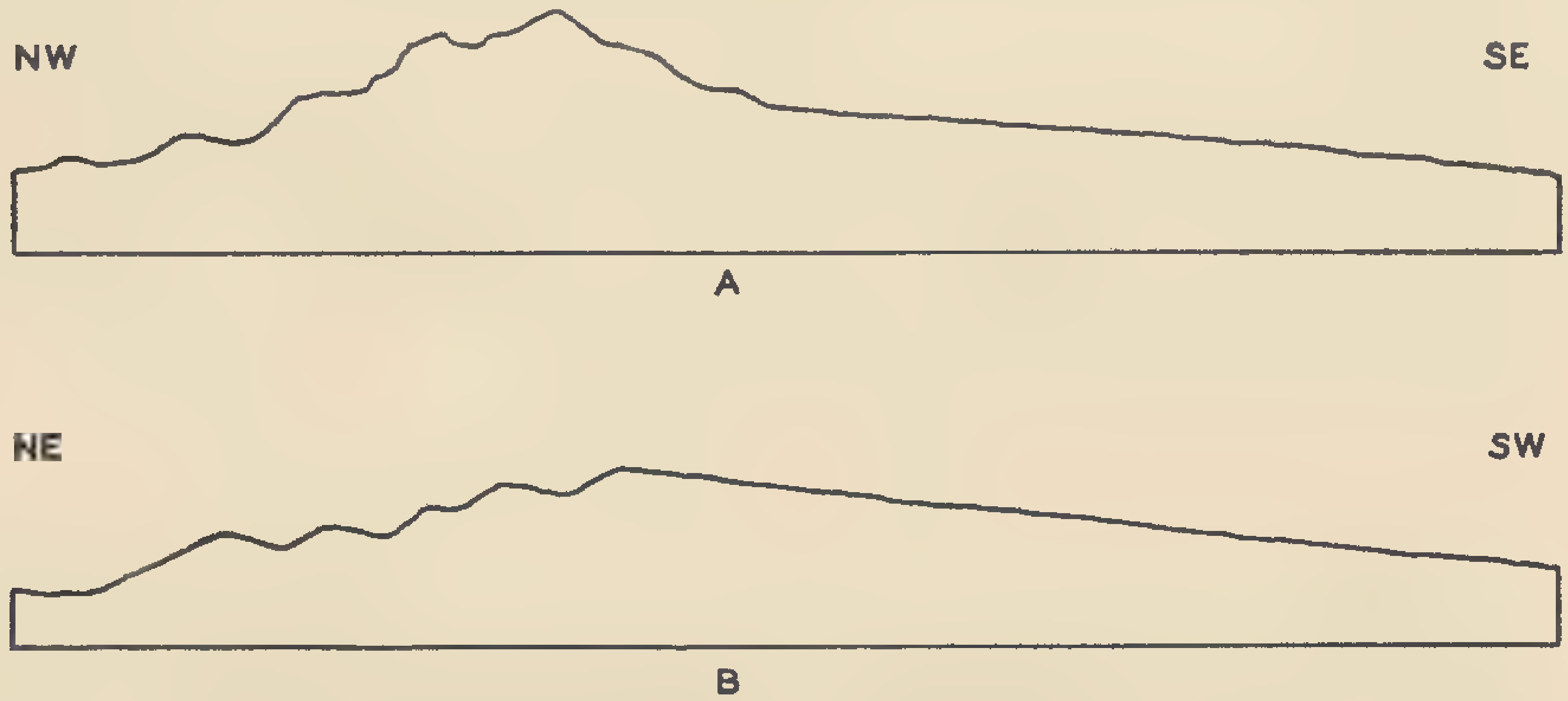

Fig. 6.—*a*. Generalized profile across the northeastern area and the great plain. *b*. Generalized profile across the western area and the great plain.

included the large boulders that it had brought from the mainland (Plate 17, fig. 2). The quantity of material in the moraine thus formed was not large, and at some places practically no material was deposited, so that pre-Wisconsin beds are now found at the surface. The larger part of the deformation of these older beds is due to earlier ice advances, and the fact that the pre-Wisconsin surface can still be recognized suggests that the Wisconsin ice overrode that surface without greatly disturbing it.

THE CAPE COD BAY LOBE

The topography and the surface deposits on the eastern half of Marthas Vineyard, including Chappaquiddick Island, are products of the action of the Cape Cod Bay lobe. They resemble in many ways those of Nantucket, although their mode of development at some places was not so simple nor so clearly marked. The eastern part of the island differs very strikingly from the western part. Its topography is much less rugged and only a few of its elevations rise more than a hundred feet above sea level. (Plate 17, fig. 1.) Its deposits consist almost entirely of sand and gravel laid down by the Wisconsin ice sheet. The Cretaceous and Tertiary strata are not exposed, and the pre-Wisconsin glacial deposits are exposed only at some places.

The southern limit of the ice in this area is marked by a well-developed ice-contact slope in the area south of Lagoon Pond. On Chappaquiddick Island this slope is well defined at but two places, and for short distances only. Elsewhere it can be traced only by the distribution of the boulders, for at many places the topography north and south of the contact is much alike. A close study of the surface, however, reveals a difference in the origin of the deposits. A poorly developed ice contact extends along a line that runs northwestward for about a mile and a quarter from a place near the shore at the south end of Poucha Pond, at the southeastern extremity of Chappaquiddick. Boulders are found along this line, the largest of them about 12 feet long. The lowland northeast of this line represents the fosse; the higher land southwest of it is a narrow fringe of outwash plain. This plain slopes toward Katama Bay and is cut by several shallow creases. The ice contact is not clearly evident in the south-central part of Chappaquiddick Island, but it can be traced by a line of boulders that curves westward toward a small marsh south of Snow's Point, where it turns rather sharply to the northwest. The fosse also is lacking for some distance here, but it reappears about half a mile east of the marsh. The outwash plain, which is interrupted only by a few creases, extends as a fringe continuously along the east side of Katama Bay.

On the opposite part of the main island, in a stretch extending northwestward nearly to the south end of Lagoon Pond, a distance of 6 miles, the ice contact can be traced by means of boulders. In this stretch there is a gradual transition from stratified moraine to outwash plain.

The limit of the Cape Cod Bay lobe south of Lagoon Pond is marked by a well-developed ice contact slope, which extends westward for about a mile and then runs northwestward for about 2½ miles. The fosse here is not wide but is well marked. North of the fosse, on the west side of Lagoon Pond, and on its east side as far as the north end of Sengekontacket Pond, there are the largest areas of stratified moraine on the island. The outwash plain is well developed south of the ice contact slope. Beginning abruptly at the crest of the slope it stretches away far to the south, declining in altitude at an average rate of 15 to 20 feet to the mile. In this area the head of the plain reaches its highest elevation, approximately 100 feet, about a mile and a half west of the head of Lagoon Pond. The plain here appears to owe its origin largely to the Cape Cod Bay lobe and not to the Buzzards Bay lobe, for nearly all its drainage lines except those in its eastern part point toward this lobe. The drainage lines in the eastern part of the plain, especially on the west side of Edgartown Great Pond, run southeastward, but they are not long, and those farther west do not cross the main creases, which run southwestward.

MORAINES

STRATIFIED MORAINES

The moraines in the western area, which some geologists have called kame moraines, are made of roughly stratified beds of sand and gravel that were deposited by water flowing from the melting ice. These moraines give this area its characteristic aspect. Many of them are ridges whose long axes extend northeastward, but some are of irregular form. Such ridges are common in the western area of Marthas Vineyard.

TILL MORAINES

On Marthas Vineyard till moraines are much less common than stratified moraines, but at many places the two kinds can be distinguished only by examining their internal structure. The till laid down by the Wisconsin ice is sandy and contains very little clay. The till moraine is rounder in form; it nowhere presents sharp cones and ridges. Typical till moraines are common in the Gay Head region.

In the northeastern area the moraines formed by the Cape Cod Bay lobe are distinctly different from those in the western area. They have no sharp ridges and cones such as are seen in stratified deposits; they show the more subdued forms of till moraines. The surface material is a sandy till containing no clay and in places no pebbles. At a few places the ridges have a central core of older till, upon which the later moraine was laid. The moraines on both sides of Lagoon Pond occupy high ground and lie above the level of the outwash plain just south of it; those farther east occupy much lower ground, and few of them are as high as the adjacent plain.

KETTLES

Kettles are numerous in both the western and the northeastern areas, and many of them are occupied by small ponds or swamps. Those in the till moraine are relatively shallow and have gently sloping sides; those in the stratified moraine are deeper, and many of them have steeper sides. The kettles of both types are merely low undrained areas between ridges built up of material laid down by the ice. Most of them are not ice-block holes, but depressions due to the arrangement of the surrounding morainal ridges. Most of the kettles in the till moraine have more regular outlines than those in the stratified moraine.

There are at least two kettle valleys on the island. One is on the west side of Lagoon Pond and the other, which is larger and contains a series of ponds, is the valley in which James Pond lies. This valley was probably formed by the building up of a series of recessional moraines rather than by buried ice. The chain of ponds, however, although it is not well shown on the topographic map, suggests a kettle valley.

OLDER VALLEYS

Conspicuous elements of the physiography of the morainal areas of Marthas Vineyard are the old valleys cut in the Manhasset deposits. Although these valleys were cut in unconsolidated beds, most of their larger features were not changed by the action of the Wisconsin ice sheet. They may be divided into two groups: (1) the more maturely developed and larger, which run southwestward, and (2) the more youthful, which are shorter and run at right angles to those of the first set.

The first valley of group 1 to be considered here heads between Prospect Hill and Peaked Hill, in the western area, and runs northeastward nearly parallel to the shore as far as North Tisbury village, where the stream now occupying it turns abruptly south. The original valley probably extended farther northeast but is now filled with outwash gravel. No single continuous stream occupies the whole valley, as the streams of group 2, working back from the coast, found shorter courses to the sea, and intercepted the older stream, diverting its water. The second valley of group 1 here considered runs parallel to the first and includes the country along the Middle Road. It starts south of Peaked Hill and is now occupied in its lower part by the Tiasquam River, west of West Tisbury. This old valley is lost under the outwash in the same way as the other valley. Whether it once extended farther northeast, toward Lagoon Pond, or joined the north valley cannot be told. The headwaters of this valley were intercepted by a brook that flows into Chilmark Pond. There is a sharp elbow of capture and a very considerable deepening of the original valley.

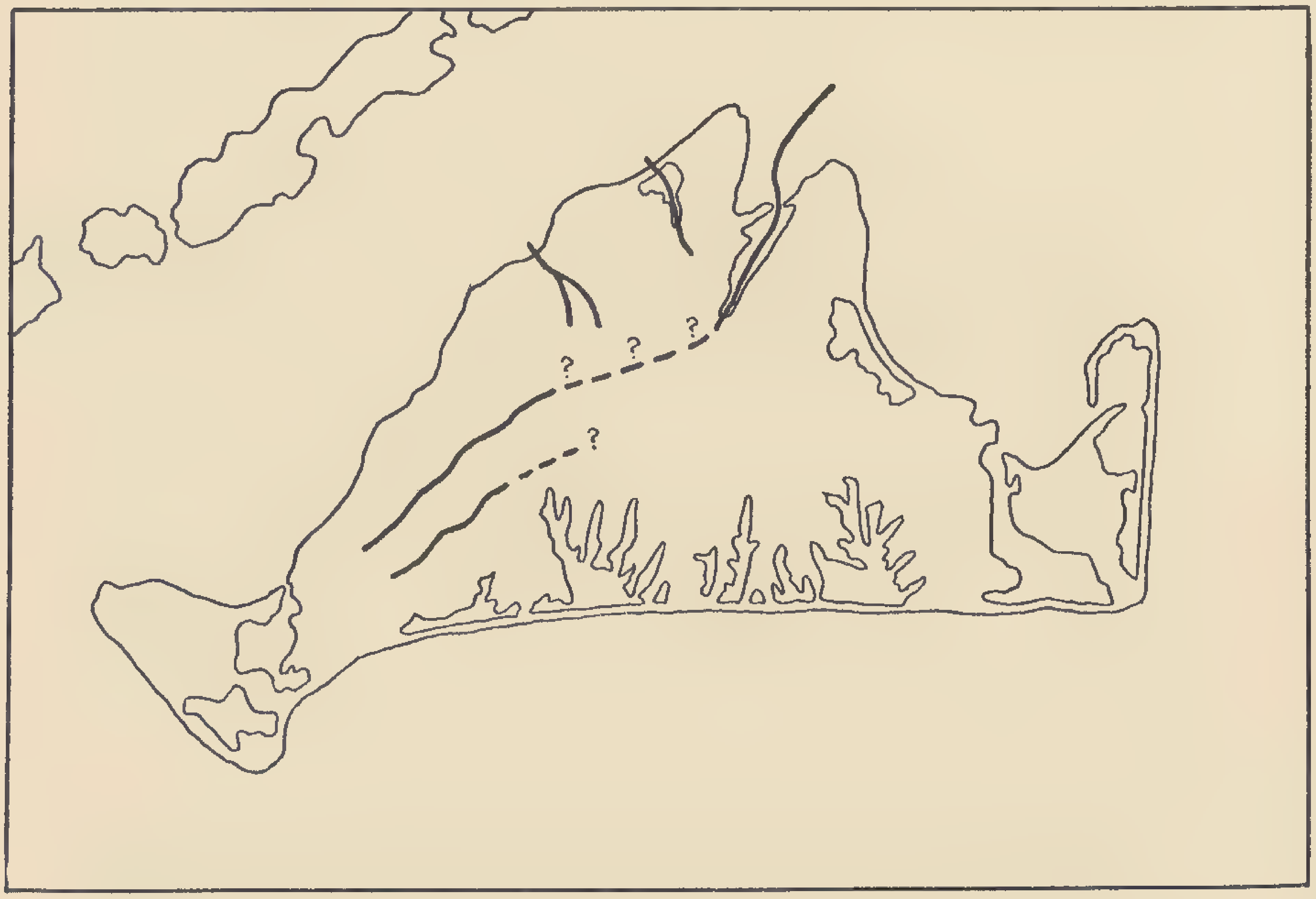

Fig. 7.— Map showing location of pre-Wisconsin valleys on Marthas Vineyard.

To this same group, and perhaps to the same drainage system, belong the now submerged and glaciated valley of Lagoon Pond (Plate **18**, fig. 1) and Vineyard Haven Harbor. The upper parts of this old river course are now obliterated by the outwash plain. The lower part has been much changed by glacial scour, for its direction is nearly parallel to the movement of the ice of the Cape Cod Bay lobe. Later wave action built a bar that nearly separates the lower part into two portions. This valley looks large for the size of the island, but when the possibility that two streams entered it from the western area is added to the fact that it has been submerged, and the probability that glaciation widened it, to say nothing of the results of wave work, it may reasonably be considered the site of an ancient river. It must also be remembered that the Vineyard interval was extremely long compared with the time that has elapsed since the Wisconsin ice sheet disappeared.

The valleys of the second group are more numerous than those of the first. Beginning on the southwest, we may say that the depression occupied by Menemsha Pond was perhaps originally connected with a drainage system that has since been submerged. In the higher ground on the northeast there are two small brooks: Roaring Brook and Howland's Brook. These have comparatively short and steep courses to the sea, and were once used for mill power. There are several other smaller brooks between them and Paul Point. At James Pond another old valley, which was described above as a kettle valley, extends well back into the moraine. It is not now occupied by a stream, but it was dammed by glacial deposits that hold the water in several small ponds.

Chappaquonsett Pond probably represents a valley that is now submerged and glaciated in its lower part and obliterated by outwash gravel in its upper part.

OUTWASH FEATURES

THE OUTWASH PLAIN

South of the two moraines lies a great triangular outwash plain formed by gravel carried out from the melting ice of the Wisconsin glacier. Its northwest side runs south-southwest, its northeast side runs southwest, and its south side runs east and west and is virtually the south shore. That it is a true outwash plain is shown by its relations to the terminal moraines, by the ice contact slopes along its northern side, by its even, gentle slope, by the channels that traverse it, and by the structure of the gravel that composes it.

ICE CONTACTS

Ice-contact slopes are well displayed along the northern edge of the outwash plain at a few places but elsewhere the plain merges into a morainal surface or breaks down into stratified moraine. At places where the ice contact is found there is a well-marked fosse containing no morainal features. At such places the relations between the plain and the moraine are those shown in Figure 8a. Where there is no ice contact slope the relations are those shown in Figure 8b.

1. About a mile north of West Tisbury post office the contact, which is well marked for half a mile, extends northeast and southwest. The fosse lies on the south side of North Tisbury Hill, and it contains several large boulders. (Plate 18, fig. 2).

2. About a mile southwest of the head of Chappaquonsett Pond there is an ice contact slope and fosse, which at its south end cannot be traced with certainty but which extends to the head of the pond, where it becomes stronger and presents the best example of this feature on the island. The slope is in places more than 50 feet high and is clearly shown by the contours on the topographic map. This contact is not at the edge of the great plain but was built by the Buzzard's Bay lobe at the edge of a local plain some distance north of the southern limit of the Cape Cod Bay lobe.

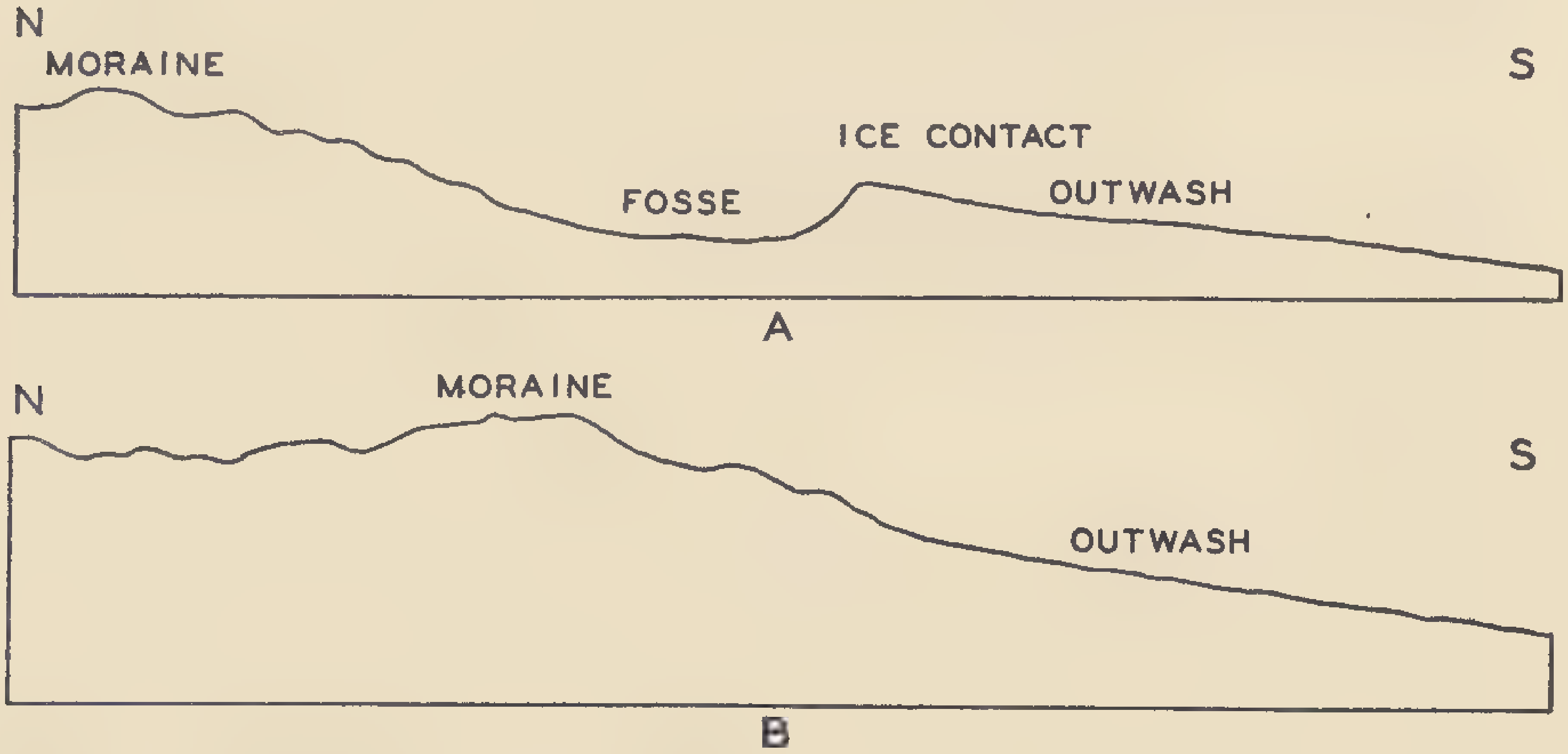

Fig. 8.—*a.* Profile showing relation of bouldery moraine and outwash plain where there is a an ice-contact slope and a fosse. *b.* Profile showing relation of bouldery moraine and outwash plain where no ice-contact slope and fosse exist.

3. The most extensive ice contact extends westward from a point about half a mile south of the head of Lagoon Pond. It can be traced for more than two miles, and it curves somewhat to the north as it approaches the state road. It is a typical, clearly marked contact slope, and throughout its course it forms the northern limit of the great plain. The fosse that accompanies it contains in its deepest part a small pond known as Duart's Pond. Unlike the two preceding contacts, this contact was made by the Cape Cod Bay lobe, and it is the only one formed by this lobe on the main island.

4. On Chappaquiddick there are two short ice contact slopes formed by the Cape Cod Bay lobe.

KETTLES

Kettles are not common in the outwash plain; indeed, with the exception of two conspicuous examples, they may be said to be absent. One of these is about a mile and a half due south of the head of Lagoon Pond, the other is about two miles west of the first. Both are large and are shown on the topographic map. One is near the house of the superintendent of the Massachusetts State Game Reservation and is occupied by a small pond. It is the larger and deeper of the two and is of very irregular outline. The other is fairly regular in outline but is little more than a broad, shallow depression. These kettles were doubtless not formed by ice blocks, for they lie farther south than the probable southern limit of the ice; though possibly the ice of early Wisconsin time may have extended southward beyond that supposed limit, and all traces of it may have been obliterated by the material laid down on the outwash plain when the ice front occupied the position marked by the contact slope south of Lagoon Pond. Or, more probably, they were once parts of the numerous channels that were cut off from the present channel by local deposits of outwash material. The last suggestion is supported by the facts that the large kettle on the State Game Reservation is not far from the head of the deep Oyster Pond Channel and that the other kettle is near the head of the former drainageway to the head of Edgartown Great Pond.

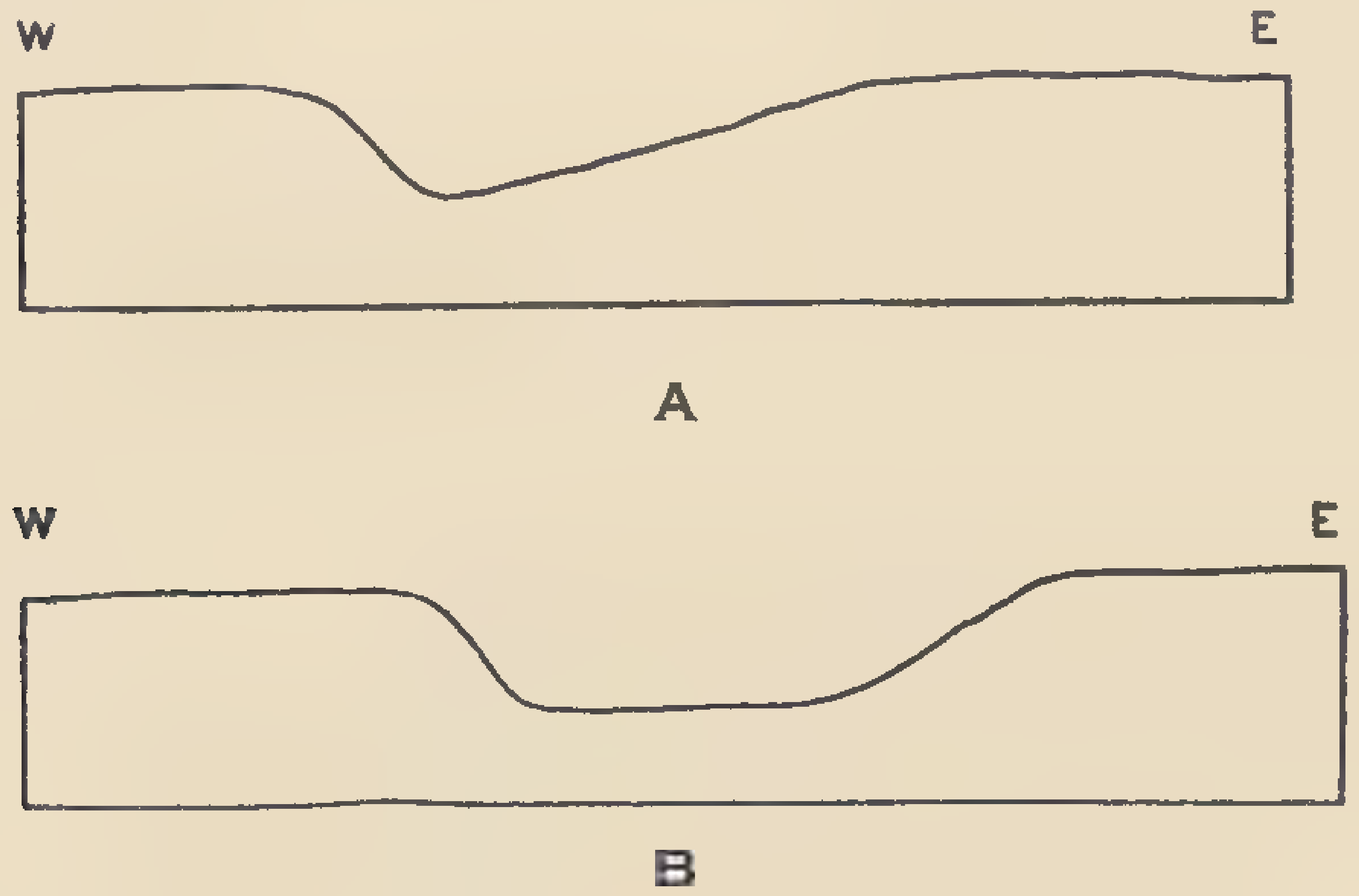

FIG. 9.— *a*. Generalized profile of a channel or crease, showing the relative steepness of the east and west bank. *b*. Profile of Watcha Pond channel, showing extreme difference in form of opposite slopes.

CHANNELS

The numerous channels or creases on the outwash plain are among the most conspicuous features of the island. Their form and distribution show that they were once occupied by streams. They now contain no running water, but their lower parts are occupied by ponds, which stand practically at sea level. (Plate **19**, fig. 1). These channels form a branching network that extends over the greater part of the plain. The only part of it in which they are not found extends along its northern margin. Some of the larger channels were evidently master streams to which the smaller ones were tributaries. The bottoms of these channels are fairly broad and flat and have an even grade from their heads down to the ponds. The banks of most of them are less than 20 feet high. The east and the west banks of many of them differ greatly in steepness, the west bank being almost invariably the steeper. This difference has been noted in many of the large northward and southward-flowing streams of the world and was long the subject of speculation. The work of G. K. Gilbert[1] and others shows that it is possibly due to the deflection of the streams by the rotation of the earth. When the forward motion of the Wisconsin ice was about balanced by the melting, a large volume of water must have been poured over what is now the outwash plain, sufficient to form streams that produced the now deserted channels and to carry material far from the melting ice. Most of these channels, even those in the western part of the plain, with the exception of Tisbury Great Pond, point toward the area occupied by the Cape Cod Bay lobe, indicating that most of the water was derived from the Cape Cod Bay lobe and that this lobe was the last one to retreat from the region. The heads of Edgartown Great Pond and Tisbury Great Pond alone suggest drainage from the Buzzards Bay lobe.

SHORE FEATURES

Marthas Vineyard, being an island and being made of unconsolidated material, has naturally many shore features that have been formed by the action of the waves, currents, and tides since Pleistocene time. The action

[1] Gilbert, G. K., The sufficiency of terrestrial rotation for the deflection of streams, Am. Jour. Sci., 3d ser., **27**, pp. 427–432, 1884. See also Lewis, E., Certain features of the valleys or watercourses of southern Long Island, Am. Jour. Sci., 3d ser., **13**, pp. 215–216, 1887.

For additional consideration of this question the reader is referred to the following articles:

Von Baer, Karl E., Ueber ein allgemeines Gesetz in der Gestaltung der Flussbetten, Bull. Imp. Acad. Sci., St. Petersburg, **2**, pp. 218–250, 353–382, 1860.

Reclus, Elisée, The earth, pp. 372–377, New York, 1872, or **2**, pp. 433–439, New York, 1871.

Bryson, John, The geological formation of Long Island, New York, with a description of the older watercourses, New York, 1885.

Cobb, Collier, Note on the deflective effect of the earth's rotation as shown in streams, Elisha Mitchell, Sci. Soc. Jour., pp. 26–32, 1893.

of these forces and of the wind have been both constructive and destructive, but destruction has been and still is predominant, and the island is, therefore, gradually being reduced in size.

CONSTRUCTIVE ACTION

The constructed forms are mainly barrier beaches, which are of different types. The cliffs supply abundant material for building beaches. The largest barrier beaches on the island are along the south shore. One continuous beach stretches from Nashaquitsa cliffs, at the west end of the island, to Wasque Point, the southernmost extremity of Chappaquiddick. The current along this shore generally runs eastward, so that the openings in the beach migrate eastward. Much of the material of this beach, at least south of Chilmark and Tisbury Great Pond, is the waste of Nashaquitsa cliffs, and some is furnished by Squibnocket cliffs. The remainder is waste from the outwash plain. This South Beach, as it is called, probably originated as an off-shore barrier beach and was forced back by the waves until it encountered the land. It now extends in a practically straight line from Chilmark Pond eastward to the south end of Chappaquiddick. The beach in front of the ponds does not bend in, and the openings that are artificially cut through the beach each year are filled within a few weeks. Natural openings have been made in this beach by the waves, especially along the south side of Katama Bay. The records of the United States Coast and Geodetic Survey[1] show openings at the west end of Katama Bay, which work farther eastward from year to year until they reach Wasque Point.

Another extensive barrier beach forms the east shore of Chappaquiddick Island, connecting it with Cape Poge. Unlike the South Beach, this East Beach is accompanied by dunes, especially along the east shore of Cape Poge Bay. This beach is probably made of material derived from Cape Poge, where the waves are actively cutting away material. No such cutting is in progress along the south shore. The East Beach is also a barrier beach behind which lies an almost continuous lagoon composed of Poucha Pond and Cape Poge Bay.

On the west side of Cape Poge there is a bar or spit that stretches southwestward in a long curve. This spit, which is made from the waste of Cape Poge, nearly shuts off Cape Poge Bay from the sea, almost converting it into a pond. Others of similar origin separate Sengekontacket Pond from the sea, and cut off Lagoon Pond from Vineyard Haven Harbor.

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[1] Whiting, H. L., Report of changes in the shoreline and beaches of Marthas Vineyard as derived from comparisons of recent with former surveys, U. S. Coast and Geodetic Survey Report for 1886, Appendix No. 9, pp. 263–266, 1887, with map. Also, same author, Topographic resurveys on Marthas Vineyard, [etc.], U. S. Coast and Geodetic Survey Report for 1889, Appendix No. 14, pp. 459–460, 1890, with map.

At the west end of the island, on the north and southwest coasts of Gay Head, there are two wide stretches of beach and dune. One extends from a point about a mile east of Gay Head cliffs to the entrance of Menemsha Pond, and its eastern part shuts off this pond from Vineyard Sound. The other extends from the south end of Gay Head cliffs to Squibnocket and encloses Squibnocket Pond. These beaches are being built forward, largely with material from the Gay Head cliffs, and are accompanied by large dunes.

Barrier beaches or bars, some of which convert former bays into ponds, are found along the shore of Vineyard Sound, especially where valleys come down to the coast. Such are the bars in front of Chappaquonsett and James ponds.

DESTRUCTIVE ACTION

Most of the forms produced by the destructive action of the waves are sea cliffs. A large part of the shore on the two northern sides of Marthas Vineyard consists of headlands that end in cliffs, between which lie stretches of beach. As these cliffs are composed of unconsolidated material, and as many of them are exposed to the action of strong waves, their appearance is considerably altered from year to year. The two largest and most striking cliffs are the Gay Head cliffs and the Nashaquitsa cliffs. Lesser cliffs are seen near Roaring Brook and at Cape Higgon, Norton Point, East Chop, Stonewall Beach, and Squibnocket.

The Gay Head cliffs, long famous for their vivid colors, are about three-quarters of a mile long and are 140 feet high at their highest point. They consist of Cretaceous clay and some Miocene and Pleistocene beds, all much folded. The material and the structure have determined in large part the picturesque forms into which they have been cut by erosion. (See Plate **14**). The more resistant beds of clay form small headlands; the less resistant beds have been cut back and form recesses, such as the Devil's Den. Landslides have determined some of the forms, although most of these are, in turn, caused by the undermining action of the waves at the base of the cliffs. The colors are due in part to the original materials in the beds and in part to the weathering of these materials, especially those containing iron oxides. All the colors have "run" more or less, for the rain washes down from the upper beds material that coats the lower ones. The Gay Head cliffs evidently once extended farther northwest, for the sea has long been cutting them back southeastward. The first lighthouse on Gay Head had to be replaced by the present one in 1858, for the encroachment of the sea made it no longer safe. A shoal extends northwestward into the sound from the cliffs. This shoal is not made of shifting sand but is underlain by the same material that forms the cliffs. On this shoal there are many large boulders, such as cover the surface of Gay Head and are seen in some of the Pleistocene deposits. These boulders were probably too large for the waves to remove at the time the sand and gravel originally associated with them were removed and were left as monuments marking the former extent of these deposits. The name "Devil's Bridge" has been given to this boulder-strewn shoal.

The Nashaquitsa cliffs, although not so strikingly colored as the Gay Head cliffs, except in small patches at their east end, are very picturesque. (Plate **20**, fig. 1). They are considerably longer, being two miles in length, and they are somewhat higher in their highest part. Their lack of the vivid colors of Gay Head cliffs is due to the absence of the Cretaceous clay and the abundance of glacial gravel and clay. The clay found here is the blue-gray Pleistocene clay. These cliffs begin at a small point at the east end of Stone Wall Beach and rise abruptly to a height of 150 feet. The cliffs remain fairly high for about three-quarters of a mile and then fall to a height of about 50 feet. From that height, with some variations, they slope down to a height of about 20 feet at their east end. These cliffs are also being cut back rapidly. According to an estimate made by the United States Coast and Geodetic Survey[1] in 1853 they are being cut back about 3 feet a year.

Of the cliffs along the northwest coast east of Gay Head, those north of Prospect Hill are the most conspicuous. They are about 120 feet high and are composed largely of beds of loose gravel and, at the base, of some Cretaceous beds and glacial clay. The differences in the character of these beds causes differences in the forms produced by the erosion of the cliffs, the Cretaceous beds eroding in ridges and gullies, with an occasional pinnacle; the beds of gravel eroding in smooth slopes at the angle of repose; and the beds of glacial clay forming vertical walls. These different materials also give different colors to the cliffs, among them notably the white of the Cretaceous beds and the blue-gray of the glacial clay. At Cape Higgon and Norton Point there are cliffs about 80 feet high, composed largely of beds of loose gravel, which are continually creeping down as the waves attack them at the base.

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[1] Rept. Supt. Coast and Geodetic Survey for 1853, p. 30, 1854. Statement by Assistant H. L. Whiting.

LANDSLIDES

At several places in the cliffs there may have been small landslides, which have involved beds of clay, probably when wet. The attitude of a bed may determine its stability; a bed in one position is more likely to slip than a bed in another. (Plate **20**, fig. 2.)

STRATIGRAPHIC GEOLOGY

Introduction

OUTSTANDING GEOLOGIC FEATURES AND OBSTACLES TO GEOLOGIC WORK

NATURE OF THE DEPOSITS

The deposits on Marthas Vineyard are unconsolidated beds laid down in late geological time. At many places they are greatly distorted, and they cover and hide all older Pleistocene beds. For this reason the boundaries of formations cannot everywhere be determined accurately, and at some places they have been drawn where the relief changes.

THE TOPOGRAPHIC MAP

The topographic base map used was made in 1887, when it was not considered necessary to represent the features in as great detail as is now essential for detailed geologic work. At many places the contouring was so greatly generalized that the character of the surface is entirely lost. Furthermore, the map is in some respects inaccurate. During the forty years that have elapsed since the map was made, there have been many changes, some due to natural causes, and some due to the work of man.

THE WISCONSIN DRIFT

The sheet of Wisconsin drift mantles all older deposits. In the morainal areas it is usually a sandy till, which at some places is as much as 6 feet thick. In the great plain it consists entirely of a thicker covering of outwash gravel. In the till-covered area the drift has only in part obliterated the older surface. In the outwash plain it has completely buried the older surface. The task of determining the location and character of the older beds in the morainal areas is therefore difficult, and in the outwash area it is at most places nearly or quite impossible.

SECTIONS IN THE CLIFFS

The cliffs afford the best sections on the island. Many of them have been almost continuously cut back by the waves and show the deposits well, except where the nature of the material causes it to slide down. The structure of a cliff as worked out one year may not be the same in later years. Many of the cliffs, especially those in which the retreat is rapid and the dip is high, change so greatly from one year to another, both as to contour and as to the beds exposed, that none of the features first seen can be found again.

SECTIONS IN THE INTERIOR

The older deposits are exposed at but few places in the interior of the island, and they show their character and structure only in fresh and fairly large exposures. The exposures consist of sand and gravel pits, a few road cuts, and pits from which clay was dug many years ago. As sand and gravel can be obtained almost anywhere on the island and are not much used, the pits from which they have been taken are small. A few cuts along the state road expose the later deposits. The old clay pits in the western morainal area help the geologist to trace the distribution of the Cretaceous beds, but they are usually filled with water, so that only the material in the dump indicates what is underground.

LITHOLOGICAL SIMILARITY OF THE PLEISTOCENE DEPOSITS

The lithological similarity of the Pleistocene beds is particularly marked in the waterlaid deposits of the Manhasset formation and in the Wisconsin deposits. These have about the same size of grain and are apparently composed of much the same material. The upper and the lower members of the Manhasset formation could not be told apart were it not for the bed of till (Montauk till member) that separates them, nor could these two beds of Manhasset gravel be distinguished from the outwash gravel of the Wisconsin stage except by considering the difference in their distribution. The Wisconsin till, although it is usually much sandier than the till member of the Manhasset, is at some places so nearly like the Manhasset till that it can be distinguished only by its position and by the fact that it is separated from the Montauk till by a bed of gravel. Where this older till contains few pebbles and is made up chiefly of reworked Gardiners clay it so closely resembles the Gardiners that it can be identified only by its position. It is not possible to distinguish the various Pleistocene deposits by differences in the amount of weathering.

LACK OF BORINGS

Well borings have been found at only two places on the island. A group of wash borings were made in the Upper Cretaceous beds near Prospect Hill to find white kaolin sand. The records of these borings were not of much assistance, especially as they were made in an area where the lower beds of the moraine have been greatly folded and probably overthrust. Borings were made near Norton Point by the Clay Products Company. The records of these borings show the presence of Cretaceous beds, but they are of no value to the geologist, for the notes showing exactly where the borings were made cannot now be found. Since the field work for this report was completed, a deep well has been sunk just east of Vineyard Haven, at the head of the harbor. This well had reached a depth of 160 feet, but no record of it is available except that it encountered no hard rock.

NATURE AND AGE OF THE PRE-PLEISTOCENE DEPOSITS

The Cretaceous and Tertiary deposits constitute all the pre-Pleistocene formations found on Marthas Vineyard. They are all unconsolidated, but otherwise they vary considerably in character. These older deposits are exposed only at Gay Head and at a few places in the western morainal area, both along the shore and inland. The beds seen are much folded and overthrust. The Cretaceous deposits comprise variegated clays and arkosic sand in which the feldspar has been altered to kaolin. According to Berry[1] these Cretaceous beds belong to the lower part of the Upper Cretaceous system. The Tertiary deposits are much less extensive and have been clearly recognized only in the Gay Head cliffs. They have been usually described as osseous conglomerate (a semi-consolidated quartzose conglomerate containing numerous cetacean bones) and greensand, though they possibly include some other sand. These beds have been much folded and overthrust and are separated from the overlying Pleistocene beds by a marked unconformity. The fossils in the sand show that it is almost entirely Miocene, though it includes some Pliocene patches. The osseous conglomerate, however, is now regarded as of early Pleistocene age. No Eocene or Oligocene deposit has been found, except possibly a few fossiliferous fragments in the glacial drift on Chappaquiddick Island.

The Cretaceous and Tertiary deposits are of interest because they are the most northerly and easterly known remnants of the beds of those ages in the

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[1] Berry, E. W., The age of the Cretaceous flora of southern New York and New England: Jour. Geol., **20**, pp. 608–618, 1915.

Atlantic coastal plain except a small amount of Miocene greensand at Marshfield, Massachusetts, and a small bed on the Elizabeth Islands. These beds were probably once continuous with those of the same age on Long Island and in New Jersey.

NATURE AND AGE OF THE PLEISTOCENE DEPOSITS

The Pleistocene beds form by far the greater part of the formations exposed on Marthas Vineyard. With the exception of some cemented patches of gravel these beds also are unconsolidated. They differ considerably in lithologic character, consisting of sand, gravel, till, and clay. They differ from the pre-Pleistocene deposits in containing unaltered feldspar. The pre-Wisconsin beds are exposed only in the western morainal area and are best displayed in the sections along the shore. The oldest Pleistocene beds are greatly folded and distorted; the later ones are much less so. The Manhasset beds are but slightly folded.

These deposits range in age from early Pleistocene to Wisconsin. At times deposition ceased and interglacial stream erosion was established. The deposits are mostly of glacial or glacio-aqueous origin, and afford evidence of four distinct advances and retreats of the ice. They cannot be certainly correlated with those of the Mississippi Valley or those of Europe, but the beds on Long Island[1] have been tentatively correlated with those on Marthas Vineyard.

The Pleistocene series of beds makes up the greater part of Marthas Vineyard, where it is more nearly complete than it is anywhere else in New England. Together with Cape Cod, Nantucket, No Mans Land, and the Elizabeth Islands, it is the only region, except a few small areas farther north, where the older Pleistocene beds are well shown. Furthermore, Marthas Vineyard has the finest exposures and the most complete series. This island, with Nantucket, also marks the southernmost stand of the Wisconsin ice sheet. It exhibits features of the terminal moraine not found elsewhere in New England, such as the interlobate character of the moraines and outwash and the effects of the overriding ice on older unconsolidated material.

PROBABLE NATURE AND DEPTH OF THE PRE-CRETACEOUS BASEMENT

The nature of the rocks composing the basement on which the beds of Martha's Vineyard rest can only be inferred from what is known of the geology of the southeastern mainland of Massachusetts. This basement probably contains no rocks later than Carboniferous, but it may possibly include some earlier Paleozoic rocks, which may be accompanied by intrusive rocks. These Paleozoic rocks are probably beds of more or less metamorphosed conglomerate, sandstone, and shale. The surface of the basement series was probably peneplaned during Cretaceous time. The depth at which this basement series lies is also unknown and can only be roughly inferred. By calculating the average slope of the hard rock surface from northern Rhode Island to the northwest shore of Buzzard's Bay and projecting this to Marthas Vineyard we get a depth of 500 to 600 feet. Only deep borings can give the depth accurately.

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[1] Fuller, M. L., The geology of Long Island, New York, U. S. Geol. Survey Prof. Paper 82, p. 220, 1914.

Cretaceous System

NAMES OF THE BEDS

No geologic name has been proposed for the series of Cretaceous beds exposed on Marthas Vineyard, but locally and commercially a part of the series has been called the "Gay Head clays." Shaler applied the term "Vineyard series" to the greater part of these beds and to the associated Tertiary beds, but he thought the whole series was of Tertiary age. Ward called them the "Island series," but this term has not been used by later writers.

SUBDIVISIONS

The beds of Cretaceous clay are so greatly folded and overthrust at the only place where they are well exposed that their subdivisions and relations cannot easily be determined. A paper by Shaler[1], published in 1890, contains a section of the Gay Head cliffs prepared by Woodworth, in which the following beds are assigned to the Cretaceous system: (1) lignite beds; (2) noduled clays and leaf beds; (3) white micaceous sand and clay. In a later paper Woodworth[2] describes all three of these beds as "non-marine lignitic and leaf-bearing clays," and added "marine sands and clays of Upper Cretaceous age." These beds of sand and clay were not clearly exposed at Gay Head, but numerous fragments of a micaceous hematitic sandstone containing Cretaceous fossils had been found at Indian Hill, 10 miles to the northwest.

Fuller[3] gives a more complete columnar section of the Cretaceous on Long Island but adds that the deposits "differ extremely in composition within short distances." Similar differences would probably be found on Marthas Vineyard were there more good exposures, but no further subdivisions can now be given than those observed by Woodworth at Gay Head, namely:

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[1] Shaler, N. S., Tertiary and Cretaceous deposits of eastern Massachusetts, Bull. Geol. Soc. America, **1**, pp. 443–452, 1890.

[2] Woodworth, J. B., Unconformities of Marthas Vineyard and of Block Island, Bull. Geol. Soc. America, **8**, pp. 197–212, 1897.

[3] Fuller, M. L., Geology of Long Island, New York, U. S. Geol. Survey Prof. Paper 82, p. 67, 1914.

4. Marine sand and clay "of Upper Cretaceous age."
3. White micaceous sand and clay.
2. Noduled clay and leaf beds.
1. Lignite beds.

> The thickness of the plant-bearing beds in the Gay Head section must be taken with due allowance for thinning and thickening in close folds and for overthrusts, as well as for the probable occurrence of the marine Cretaceous at the summit of the pre-Tertiary series. One hundred and fifty feet is probably in excess for the beds exposed above sea level.[1]

This estimate includes only the contorted beds exposed in the Gay Head cliffs, beneath which, according to the estimate of the depth of bed rock, there are 500 or 600 feet more of undisturbed beds.

CHARACTER OF THE DEPOSITS

The Cretaceous deposits are unconsolidated and consist largely of clay, the largest constituent of which is kaolin. They vary slightly in composition and greatly in color. The colors are due largely to the weathering of forms of iron and other extraneous material in the clay. Many beds of red and brownish clay would be bluish gray or light gray if unweathered. Some beds that contain marcasite have assumed, on weathering, a bright yellow color, due to a coating of alum. Some beds of the purer clay are almost white; some beds of the impure clay, such as the lignitic beds, are black. All the beds of lignite contain clay, but parts of some of them consist of fairly pure lignite. The extensive white beds seen at Gay Head and elsewhere are composed of grains of kaolin and quartz and scales of muscovite, a mixture suggesting transported arkose in which the feldspar has been altered to kaolin and muscovite.

All the deposits, and even the fossil plants, are very similar to those of the Cretaceous age in New Jersey.

SOURCE OF MATERIALS

The nature of the materials composing the Cretaceous deposits on Marthas Vineyard makes it possible to form a picture of the conditions there when they were laid down and to determine, at least tentatively, the area from which the materials were brought.

The lowest Cretaceous subdivision except a small amount of lignite is nearly all clay, some of which carries fossil leaves. This material must have come from a land surface that was being elevated and subjected to erosion after a long period of atmospheric weathering as a peneplain. The great quantity of clay deposited must have been derived from feldspathic rock, such as granite and other igneous rock, or from feldspathic sandstone or shale. If it was derived from sandstone or shale the period of weathering was shorter. It might even have been eroded from these rocks without weathering and later altered to clay. If the materials are considered in connection with those of the next higher deposits, it would seem that the weathering preceded the erosion, and that they were not removed at once, as the gradient was too low to permit their rapid transportation.

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[1] Woodworth, J. B., Unconformities of Marthas Vineyard and of Block Island, Bull. Geol. Soc. America, 8, p. 200, 1897.

The beds of kaolin-mica sand represent a continuation of the conditions and processes favorable to the deposition of clay. They indicate that the relative elevation of the land was rather rapid, so that the remaining products of alteration were swept away quickly and laid down as cross-bedded deposits in shallow water. The presence of quartz grains shows that the region undergoing erosion was originally composed of granitic rock. Such a region—that is, one composed largely of granite that had been long subjected to weathering and was being reduced to a peneplain—is found in New England to the north and west of Marthas Vineyard. As to the origin of the lignite, however, which forms the lowest Cretaceous beds exposed, two theories may be advanced. The first is that they were formed in large fresh-water or brackish-water swamps from vegetation that grew and died and accumulated, without much decay, to considerable depths in the places where they now lie. To this vegetable matter a small amount of fine inorganic material was added by streams. The second theory advanced to explain the origin of the lignite is that the material now compositing it grew elsewhere and was brought to its present site by streams and deposited in lagoons. Both theories have supporters, but the first is favored here, although the beds contain no tree trunks or other like forms such as we should expect to find if the lignite had been formed where it is found, and all the fragments are considerably waterworn. Those who adopt the second theory must hold that the lignite was brought to its present site by lowland sluggish streams; otherwise more inorganic material would have been brought in and mixed with the vegetable matter. The lignite must have been deposited in large swamps or shallow lagoons in which organic material collected, together with a small quantity of fine silt, which formed clay.

RELATION OF THE CRETACEOUS TO OLDER DEPOSITS

The contact between the Cretaceous and the basement rocks is nowhere seen on Marthas Vineyard, and the relations between the two must be inferred from their relations at other places. The lowest Cretaceous deposit doubtless lies almost undisturbed upon the eroded surface of older rocks; it has probably not been dislocated by the shove and drag of the Pleistocene ice sheets. In other words, the lower Cretaceous beds lie on the older rocks here just as they do in the coastal plain to the south, although the Upper Cretaceous beds have been more or less disturbed by the action of the ice.

STRUCTURE

The structure of the Cretaceous beds is well disclosed only at Gay Head, but traces of similar structure may be seen throughout the western area. At Gay Head (Plate **19**, fig. 2), where the details of the structure have been carefully worked out by Woodworth,[1] the beds lie in a series of closely folded anticlines and synclines and are strongly overthrown to the southwest. The beds have not only been folded but have been overthrust, so that the structure is very complicated, as shown in Figure 10. At and near Gay Head the dip of the beds is fairly high, averaging over 45°, and is almost uniformly to the northeast. In the region between Menemsha Pond and Chappaquonsett Pond the dip is not easily determined, but the strike is always northeast, so that the general dip is probably northwest. In this region the dip appears to be very steep, but in the eastern part of the island it is generally slight.

The Upper Cretaceous beds seem to have been deformed by the thrust and drag of the earlier ice advances. The idea that glacial thrust was competent to deform them was first suggested by F. J. H. Merrill[2] in 1886, and is now generally adopted instead of the mountain-building theory advocated by Shaler. Merrill thought that the high elevation of some of the ridges of the terminal moraine on Long Island could be accounted for only by supposing that some of the underlying older beds had been raised to their present positions by glacial action. These older beds are thrown into a series of folds, which run at a right angle to the line of glacial advance. Hollick[3] held the same view in regard to the structure of these beds and has summed up his reasons for holding it as follows:

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[1] Woodworth, J. B., Unconformities of Marthas Vineyard and of Block Island: Geol. Soc. Am. Bull., **8**, pp. 197–212, 1897.

[2] Merrill, F. J. H., On the geology of Long Island, Ann. New York Acad. Sci., **3**, pp. 341–364, 1886.

[3] Hollick, Arthur, Dislocations in certain portions of the Atlantic coastal plain strata and their probable causes, Trans. New York Acad. Sci., **14**, pp. 8–20, 1895.

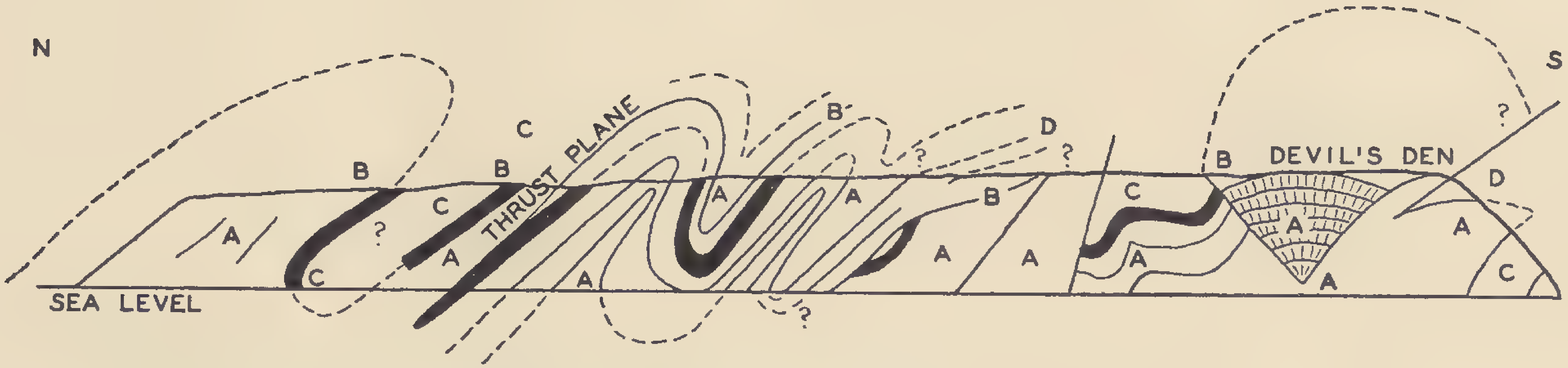

Fig. 10.— Cross section of Gay Head Cliffs showing geological structure. (After J. B. Woodworth.)
A, Upper Cretaceous clay, sand, and gravel; *B*, Miocene greensand and Pliocene beds; *C*, older Pleistocene deposits, including, in ascending order, Aquinnah (osseous) conglomerate, Dukes boulder bed, stony blue clay, and gravel bed, the last two correlated with the Manetto formation; *D* thrust planes and faults.

(1) The line of disturbance is coincident with the line of the terminal moraine from Nantucket to northern New Jersey; (2) the beds are folded and crumpled only where the moraine has advanced over some part of the coastal plain; (3) folding and crumpling cease abruptly where the moraine bends away from or leaves the plain. To these reasons may now be added another: deep borings on Long Island show that the beds below those that are folded are much less disturbed. The chief obstacle seen by Shaler to the theory of ice folding was the fact that the pre-Wisconsin surface, formed during the Vineyard interval, was very little disturbed by the Wisconsin ice. Shaler thought that if the ice could override the region without altering the surface, it was hardly possible that it would compress the underlying beds into close folds. The fact that there had been earlier and more vigorous ice advances before the Wisconsin stage was then not clearly recognized.

CONDITIONS DURING DEPOSITION

The conditions that prevailed on Marthas Vineyard while the Cretaceous deposits were being laid down, as shown by the character of the successive beds, indicate progressive subsidence and the formation of land wash. Early in Upper Cretaceous time the land that stood on the site of the island was low and poorly drained and contained fresh-water swamps. Plants grew in and around these swamps and their remains formed most of the material deposited. As time went on, more clay was brought in, probably because of differential tilting of the land, which increased the gradient of the streams that ran into the areas of deposition. The land was doubtless sinking, for in the later deposits signs of vegetation gradually became scarcer, and then only horizontal layers of clay containing a few leaves were laid down, the deposits indicating an increasing distance from the area of erosion. At this time the streams must have been made very turbid by the material they brought in, evidently from a region that had long lain at a low level and that had been subject to atmospheric weathering. Gradually the land must have stopped sinking and the areas of deposition must have become increasingly shallower, for the succeeding deposits show cross-bedding. The erosion of the land was accelerated, for the deposits became coarser, and grains of quartz and flakes of mica were mixed with the clay. Finally parts of the region must have subsided and have been invaded by the sea, for the deposits contain marine fossils. The record of Cretaceous time on the island is incomplete; it includes, perhaps, not much more than the first half of Upper Cretaceous time.

DISTRIBUTION

Most of the Cretaceous beds are found in the western morainal area. From Gay Head northeastward nearly to North Tisbury beds of Cretaceous clay are exposed at many places, especially along the valley traversed by the North Road. Some Cretaceous beds are exposed north of this valley, in the Indian Hill region, beyond which none are seen except at a place near Norton Point, where a large clay pit reveals them again. In nearly all this western area they are covered by Pleistocene deposits. Cretaceous beds are not found above sea level east of Chappaquonsett Pond.

GAY HEAD

As has already been noted, the largest exposures of beds of Cretaceous clay are in the Gay Head cliffs (Plate 19, fig. 2), where they may be seen in a section over a mile long. Here may be found the whole series so far as it is known, beginning with the beds of lignite, upon which lie the beds of clay and white kaolin sand. The section has been gullied considerably and presents much the same form as a cliff in a badland region. The colors of the beds here are strikingly brilliant. Upon the Upper Cretaceous clay lie the Miocene greensand and some Pliocene sand, which is in turn overlain by Pleistocene deposits. The thickness of the Cretaceous beds exposed here is exceedingly difficult to estimate on account of complicated folding and overthrusting, but it probably nowhere exceeds 100 feet.

CLAY PIT NEAR MENEMSHA POND

The nearest good exposure of Cretaceous beds east of the Gay Head cliffs is in an old clay pit half a mile west of the northwest corner of Menemsha Pond. This pit, one of the largest on the island exposes white kaolin sand and some red clay. The sand is overlain by the Montauk till. The red clay, which flanks the white sand on the northeast, lies below the Montauk till, as if it had been dragged up by the ice. The white sand exposed in this pit forms a bed about 20 feet thick. It is cross-bedded and very gently warped into an anticline having an axis extending east and west.

MENEMSHA CREEK

About a quarter of a mile east of Menemsha Creek, in a road cut on the north side of the North Road where it descends a steep hill east of the creek, there is a small exposure of Cretaceous white kaolin sand over clay. Above it is Wisconsin till.

SQUIBNOCKET

Along the cliffs that form the greater part of the coast of Squibnocket, especially at its northeast end, there are obscure traces of beds of red clay that have been considerably disturbed, and perhaps have been reworked, so that they may be more properly classed as Montauk till.

NASHAQUITSA CLIFFS

Near the east end of the Nashaquitsa cliffs, in Chilmark, there are exposures of Cretaceous clay, both red and white, overlain by white kaolin sand. As seen about two-thirds of a mile west of the east end, these are both gently folded and are apparently overthrust on the older Pleistocene gravels. The last third of a mile shows mostly clay, evidently considerably disturbed and overthrust on glacial gravels.

PEAKED HILL PIT NO. 1

Between the north and middle roads in Chilmark, half a mile south of Peaked Hill, there is an old clay pit that exposes the white clay and the kaolin sand. The pit extends northeastward along the strike of the beds, but its sides have fallen in to such an extent that the structure of the beds cannot be made out.

ROARING BROOK

On the northwest shore, about a quarter of a mile west of Roaring Brook, there is an exposure of a Cretaceous bed high in the cliffs. This bed was recently worked for kaolin. It includes both white kaolin sand and red clay, and it underlies a thick series of beds of glacial gravel. The strike of the Cretaceous bed is nearly parallel to the shore. The dip, although it is not at all clearly shown, seems to be toward Vineyard Sound.

PEAKED HILL PIT NO. 2

Half a mile east of Peaked Hill there is another old clay pit showing Cretaceous kaolin sand and clay. This also is badly slumped.

NORTH ROAD VALLEY

Northeast of the localities mentioned there are many small exposures of Cretaceous deposits, chiefly in old clay pits along the North Road Valley. The kaolin sand is the most common member exposed in these pits, but beds of clay are also seen. The lignite bed was not seen at any of these places. No Cretaceous beds are exposed along the shore of Vineyard Sound between Roaring Brook and Norton Point.

MAKONIKEY

About half a mile east of Norton Point, at a place known locally as "Makonikey," there is a clay pit which has been recently worked. The clay here, although undoubtedly Cretaceous, has a somewhat different appearance from that worked elsewhere. This difference may be due in part to its fresh exposure, or the bed may be different from those exposed elsewhere. The clay is a light blue-gray, or even a slightly greenish gray. It has been used for making yellow bricks. The kaolin sand is also found here, but it has not been worked. Mr. Roy Matthews, the former superintendent of the clay works, says the beds of lignite have been encountered near the pit. The section at Norton Point contains beds of lignite. Unlike most of the Cretaceous deposits exposed, these beds appear to be but little disturbed and lie nearly horizontal. Shallow borings in this vicinity strike Cretaceous beds.

Other localities at which Cretaceous beds are exposed are shown on the map. Many of these exposures are small, but they show the distribution of this series.

FORM OF THE SURFACE

The surface of the Cretaceous deposits as it existed before the Tertiary deposits were laid down is shown only in the beds exposed in Gay Head cliffs. The Cretaceous beds appear not to have been then deformed as they now are. They were undoubtedly much eroded before the beginning of Miocene time, but they probably formed an eastern extension of the features of the coastal plain, such as may still be seen southwest of the glaciated area in northern New Jersey. The occurrence in the Cretaceous section of beds of quartz gravel interstratified with beds of clay and lignite suggests that the Coastal Plain became somewhat dissected during the earlier stages of erosion in the period of uplift between the retreat of the sea at the end of Cretaceous time and the beginning of the local Miocene marine invasion. Streams that run parallel to the coast formed bluffs that sloped gently seaward from their crests. Across such coastwise cuestas the master streams maintained consequent courses to their mouths. No recognizable trace of this relief now remains in the district.

AGE AS SHOWN BY FOSSILS

Owing to the abundance of Tertiary fossils at the Gay Head cliffs and the fact that little importance was attached to the less conspicuous fossil plants as horizon markers, the early American geologists regarded the Upper Cretaceous beds as Tertiary. Even Sir Charles Lyell[1], who visited Gay Head in 1842, saw no evidence of the existence of Cretaceous beds, and Shaler,[2] as late as 1888, regarded all the beds in the Gay Head section below the drift as Tertiary.

The similarity of the beds at Gay Head to those at Raritan Bay, New Jersey, was recognized by some, but it remained for White[3] to show their age beyond a doubt. The result of White's work was later confirmed and elaborated by Hollick,[4] and four years later the extent of the Tertiary was made out by Dall.[5] More recently Bibbins[6] and Berry[7] have placed the leaf-bearing Cretaceous deposits of Marthas Vineyard in the Magothy, the second subdivision of the five Cretaceous formations now recognized in the Atlantic coastal plain, as shown in the following table.[8]

Upper Cretaceous	Rancocas	Marine
	Monmouth	
	Matawan	
	Magothy	Non-marine (estuarine and fluviatile)
	Raritan	

THE MATAWAN MARINE FAUNA[9]

A search for traces of the marine fauna found by Shaler in the fragments of ferruginous sandstone on the south side of Indian Hill near the site of Woods Schoolhouse soon brought to light numerous fragments of rather similar material, which is found as far west as Gay Head in the older drift west of the Devil's Den and to the east throughout the length of the island in the region of ice-laid drift. As noted in the accompanying report on the identification of the fossils by L. W. Stephenson, the material is poorly preserved, but in his opinion it resembles closely the fauna of the Matawan beds of the coastal plain in Maryland. The distribution of the erratic material does not show whether it was derived from layers above or beneath the lignitic and leaf-bearing clays referred to the Magothy formation, but the known facts justify its reference to the beds overlying the Magothy on Marthas Vineyard.

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[1] Lyell, Charles, On the Tertiary strata of the island of Marthas Vineyard in Massachusetts, Proc. Geol. Soc. London, **4**, pp. 31–33, 1842–43. Also Am. Jour. Sci., **46**, pp. 318–320, 1844.

[2] Shaler, N. S., The geology of Marthas Vineyard, Mass., Seventh Ann. Rept. Geol. Survey, pp. 297–363, 1888.

[3] White, David, On Cretaceous plants from Marthas Vineyard, Am. Jour. Sci., 3d ser., **3**, pp. 93–101, 1890.

[4] Hollick, Arthur, The Cretaceous flora of southern New York and New England, U. S. Geol. Survey Mon. 50, 1906.

[5] Dall, W. H., Notes on the Miocene and Pliocene of Gay Head, Marthas Vineyard, Mass., Am Jour. Sci., 3d ser., **48**, pp. 296–301, 1894.

[6] Bibbins, A. B., Occurrence of the Magothy formation on the Atlantic Islands, Abstract in Bull. Geol. Soc. America, **21**, p. 672, 1910.

[7] Berry, E. W., The age of the Cretaceous flora of southern New York and New England, Jour. Geol., **23**, pp. 608–618, 1915.

[8] Clark, W. B., Upper Cretaceous, Maryland Geol. Survey, 1916.

[9] Note by J. B. Woodworth.

The plant-bearing Magothy beds appear chiefly in the lower parts of the island, as in the Gay Head cliffs, on the terrace at Makonikey, and in the sea-shore cliffs near Cape Higgon and westward toward Menemsha. These tracts of Cretaceous appear to be wholly or chiefly Magothy, and the uplands, from Prospect and Peak Hill eastward into Indian Hill, where overlying Cretaceous sands and clays, apparently without lignites, have been folded up, may represent the Matawan and be the source of the fossiliferous marine blocks. The abundance of the material nearly in place near Indian Hill points to this conclusion.

The fossil marine fauna found by Shaler[1] in loose fragments of sandstone in the drift at Indian Hill and at Lagoon Pond are referred to the Cretaceous. The genera are given in the following list. Owing to the fragmentary nature of the material most of the specific names were not given. All are figured.

Plicatula or *Ostrea*
Ostrea or *Exogyra*
Exogyra
Cardium ?
Lucina
Tellina (*Linearia*) *?*
Lucina ?
Camptonectes burlingtonensis Gabb.
Camptonectes parvus Whitfield (*?*)
Modiola ? (2)
Anomya ?
Nuculana
Pteria
Turritella (*Nerina*)
Turritella
Cerithium
Chemnitzia
One thought to be a new genus

The determination of these fossils was confirmed by C. A. White, who, in a later paper,[2] correlated the beds in which they occur with the Tombigbee sand of Alabama, and stated that they could be provisionally referred to the base of the marine division of the Cretaceous of the Atlantic border.

REPORT ON COLLECTION OF UPPER CRETACEOUS INVERTEBRATE FOSSILS FROM MARTHAS VINEYARD, MASS.

By L. W. Stephenson

Collection made by David White in August, 1890

U. S. G. S. Coll. 788. Lagoon Pond, 2 miles above Vineyard Haven, Marthas Vineyard, Mass.

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[1] Shaler, N. S., On the occurrence of fossils of the Cretaceous Age on the island of Marthas Vineyard, Mass., Bull. Mus. Comp. Zoöl., Harvard Univ., Geol. ser. 2, **16**, No. 5, pp. 89–97, pl. 1 (map), pl. 2 (fossils), 1889.

[2] White, C. A., A review of the Cretaceous formations of North America, U. S. Geol. Survey Correlation papers, Bull. 82, p. 93, 1891.

Matrix: Dark red, fine, micaceous ferruginous sandstone, probably a sandy oxidized iron carbonate concretion. Some of the pieces have a hard, greenish-gray, only slightly weathered center containing scattered grains of glauconite.

Ostrea sp. (Same as in U. S. G. S. Coll. 1638, p. 2.)
Paranomia scabra (Morton)?
Plicatula sp. (See Shaler's figs. 2, 2a, Pl. 3.)[1]
Pecten cf. P. argillensis Conrad
Corbula cf C. carolinensis Conrad

Collections made by J. S. Diller in 1894

U. S. G. S. Coll. 1,639. Highland Bluff, Marthas Vineyard, Mass.

Matrix: Dark red, fine, micaceous, ferruginous sandstone, probably oxidized sandy iron carbonate concretions.

Anomia argentaria Morton? (See Shaler's figs. 6, 13, Pl. 2.)
Modiolus, probably a new species (See Shaler's figs. 17, 18, Pl. 2.)
Undetermined fragments of oysters and other bivalves

U. S. G. S. Coll. 1,638. Oklahoma cliffs, Lagoon Pond, Marthas Vineyard, Mass.

Matrix: Same as preceding.

Ostrea sp. A small Gryphaea-like form, probably undescribed. (See Shaler's fig. 16, Pl. 2.)
Exogyra ponderosa Roemer?
Paranomia scabra (Morton)?

U. S. G. S. Coll. 1,637. Red sandstone mound near Indian Hill, near Woods schoolhouse, Marthas Vineyard, Mass.

Matrix: Medium coarse, red micaceous ferruginous sandstone, with some small pebbles of quartz.

Gervillia (?) probably a new species. (Probably the same as Shaler's fig. 1, Pl. 2.)
Exogyra ponderosa Roemer?
Ostrea sp.

Collections sent to the United States National Museum, Nov. 9, 1904, by J. B. Woodworth. Accession number 43432.

U. S. G. S. Coll. 9,870. Cape Higgon, Marthas Vineyard, Mass. A loose block collected by J. B. Woodworth.

Matrix: Dark red, fine micaceous ferruginous sandstone, probably an oxidized concretion of iron carbonate.

Ostrea sp. (Same as in U. S. G. S. Coll. 1638, p. 2.)
Exogyra ponderosa Roemer? (One medium-sized individual, apparently smooth.)
Plicatula sp. (See Shaler's figs. 2, 2a, Pl. 2.)
Modiolus n. sp. (Same as in U. S. G. S. Coll. 1639, p. 2.)
Crassatellites sp.

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[1] Shaler, N. S., Bull. Mus. Comp. Zoöl., Harvard Univ., Geol. ser. 2, **16**, pp. 89–97, 1889.

U. S. G. S. Coll. 9,572. Chilmark, Marthas Vineyard, Mass. Collected by A. F. Foerste, Sept., 1889.

Matrix: Coarse red ferruginous sandstone, with small quartz pebbles. Unidentified pelecypods.

U. S. G. S. Coll. 9,569. From Indian Hill near the site of an old schoolhouse, Marthas Vineyard, Mass. Collected by J. B. Woodworth, June 18, 1889.

Matrix: Medium coarse ferruginous sandstone.
Ostrea sp. (Same as in U. S. G. S. Coll. 1638, p. 2.)
Exogyra sp.
Gervilliopsis?
Corbula sp.

U. S. G. S. Coll. 9,571. Lagoon Pond, Marthas Vineyard, Mass. Collected by L. F. Ward, Aug. 7, 1889.

Matrix: Dark red, fine, micaceous ferruginous sandstone, probably an oxidized iron carbonate concretion.
Ostrea sp. (Same as in U. S. G. S. Coll. 1638.)
Pecten cf. *P. argillensis* Conrad.
Paranomia?

U. S. G. S. Coll. 9,568. A boulder on Gay Head cliffs, Marthas Vineyard, Mass. Collected by J. B. Woodworth, June 1889.

Matrix: Medium coarse, micaceous ferruginous sandstone, with small quartz pebbles.
Gervilliopsis?
Ostrea sp. (Same as in U. S. G. S. Coll. 1638, p. 2.)
Exogyra ponderosa Roemer?
Pecten cf. *P. argillensis* Conrad
Cardium sp.
Corbula cf. *C. carolinensis* Conrad
Small unidentified gastropods

The fossils listed above were all obtained in pieces of ferruginous rock. Though showing a general similarity in lithologic appearance these rocks may nevertheless be divided into two types, which are probably different facies of the same formation. One facies consists of dark red, fine micaceous ferruginous sandstone, probably the oxidized product of concretionary sandy masses of iron carbonate. Some of the specimens have a dark greenish-gray, only partly weathered core; some possess the contraction cavities characteristic of septaria, and many of the cavities are lined with small crystals. The localities of this facies are:

U. S. G. S. Coll. 9,571.	Lagoon Pond
U. S. G. S. Coll. 788.	Lagoon Pond, 2 miles above Vineyard Haven
U. S. G. S. Coll. 1,638.	Oklahoma Cliffs, Lagoon Pond

U. S. G. S. Coll. 1,639. Highland Bluff
U. S. G. S. Coll. 9,570. Cape Higgon

The other facies is medium coarse, red micaceous ferruginous sandstone, containing small quartz pebbles. The specimens were collected at the following places:

U. S. G. S. Coll. 9,573. Chilmark
U. S. G. S. Coll. 9,569. Indian Hill, near the site of an old schoolhouse
U. S. G. S. Coll. 7,568. Gay Head cliffs

If the fossiliferous ironstones were all collected from the same formation the fauna as a whole includes the following forms.

List of Cretaceous invertebrate fossils from Marthas Vineyard in the collections of the U. S. National Museum and the U. S. Geological Survey

Gervillia? (Probably the unnamed species figured by Shaler as Plate **2**, fig. 1.)
Gervilliopsis?
Ostrea sp. (A small *Gryphaea*-like form, probably the same as Shaler's Plate **2**, fig. 16.)
Exogyra ponderosa Roemer? (Small and medium-sized specimens of a smooth form.)
Pecten cf. *P. argillensis* Conrad. (Costae broader and coarser than those of *P. belliculptus* (Conrad.) Same as Shaler's Plate **2**, figs. 8 and 9.
Plicatula sp. (Same as Shaler's Plate **2**, figs. 2 and 2a, probably undescribed.)
Anomia argentaria Morton? (Probably Shaler's Plate **2**, figs. 6 and 13.)
Paranomia scabra (Morton)
Modiolus sp. (Sculpture and form well preserved; probably undescribed; same as Shaler's Plate **2**, figs. 17 and 18.)
Crassatellites?
Cardium sp.
Corbula cf. *C. carolinensis* Conrad.
Corbula sp.
A small unidentified *gastropod*. (Probably Shaler's Plate **2**, fig. 10.)

Shaler's illustrations[1] indicate the following forms in addition to those listed above: *Pteria* (fig. 5); *Lucina* (fig. 11); *Cerithium*? (fig. 12); and *Turritella* (figs. 7, 14).

Subsequent to 1889 a collection of Cretaceous fossils from Marthas Vineyard, evidently obtained from the same source as the fossils listed above, was submitted to Dr. T. W. Stanton, who prepared the following unpublished report, the original copy of which he has kindly placed at my disposal:

> The fossils from Marthas Vineyard sent by Prof. Battey for examination are mostly imperfect casts and obscure impressions that cannot be determined. Numbers 1–3, 17, 31–33 and 35–37 are of this nature. Most of the forms have been figured, without specific names,

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[1] Shaler, N. S., Bull. Mus. Comp. Zoöl., Harvard Univ., Geol. ser. 2, **16**, pp. 89–97, pl. 1 (map); pl. 2 (fossils), 1889.

by Prof. N. S. Shaler in the Bulletin of the Museum of Comparative Zoölogy, Geol. ser. 2, **16**, No. 5, 1889, Plate **2**, to which references are made below.

No. 4. Apparently a fragment of a large gastropod belonging to the Volutidae.

Nos. 6 and 9. *Modiola.* (Prof. Shaler's fig. 18, and perhaps 17.)

Nos. 7 and 8. Impressions of a *Plicatula* or a *Placunanomia.* Resembles *Placunanomia lineata* Conrad.

No. 15. Undetermined. (Prof. Shaler's fig. 1.)

No. 16. Impressions of *Turritella, Corbula,* and another small lamellibranchs.

No. 18. *Exogyra*? (Possibly the same as Prof. Shaler's figs. 19 and 20, though his specimens seem to be without plications. This species has some resemblance to the Eocene *Ostrea compressirostra.*)

No. 19. *Avicula.* (Apparently not the same as Prof. Shaler's fig. 5. Compare *Avicula petrosa* Conrad.)

No. 20. *Ostrea.* (Prof. Shaler's fig. 16.)

No. 30. Fragments of wood in sandstone.

No. 34. *Modiola* and *Anomia.*

No. 38. *Lucina*? (Prof. Shaler's fig. 11.)

No. 8. bis. Boulder full of *Ostrea* sp.

Dr. Stanton does not know what disposition was made of this collection, but presumably it was returned to Prof. Battey.

The specimens named in the foregoing lists are poorly preserved and the specific determinations are doubtful, but they throw some light on the age of the formation from which the ferruginous masses were derived.

The small *Gryphaea*-like oyster appears to be unlike any oyster heretofore found in the Atlantic and Gulf coastal plain.

The identification of *Exogyra ponderosa* Roemer is fairly satisfactory and probably indicates a position within the *Exogyra ponderosa* zone.

The sculpture of the *Pecten,* which is compared to *P. argillensis* Conrad, is well preserved and is very close to that of typical examples of the species from the Ripley formation (*Exogyra costata* zone) of Tippah County, Miss. The range of the species is not sufficiently well known to serve as a basis for correlation.

Anomia argentaria Morton is a wide-ranging form in the zones of *Exogyra ponderosa* and *Exogyra costata.*

Paranomia scabra is common to the *Exogyra costata* zone and the upper part of the *Exogyra ponderosa* zone but has not been reported in the lower part of the *Exogyra ponderosa* zone.

Specimens of *Corbula* like that here compared to *C. carolinensis* Conrad have not been reported from deposits younger than the zone of *Exogyra ponderosa.*

The evidence afforded by the invertebrates seems to favor the Matawan age of the deposits in which the fossils were originally embedded, but it is in-sufficient to determine the division of the Matawan to which they should be referred. If the *Exogyra* is correctly referred to *Exogyra ponderosa,* the deposits certainly fall within the zone of *Exogyra ponderosa.* The stratigraphic limits of this zone in New Jersey appear to correspond approximately with those of the Matawan, though the lower limit of the zone has not been definitely established.

The Cretaceous plants from Gay Head and Nashaquitsa cliffs are in septarian ferruginous concretions, which are similar to those that contain the invertebrates, except that they are less hackly, splitting with smoother surfaces, and the cavities appear to lack the drusy linings seen in the masses containing invertebrate fossils. Most of the concretions are dark red, fine to medium grained, and micaceous, and some are strongly micaceous.

The plant-bearing concretions have been correlated by Hollick with the Raritan ("Amboy clay") of New Jersey, but, as the invertebrate-bearing concretions contain no fossil plants except an occasional obscure stem, the plants and invertebrates were probably not derived from the same source. The two kinds of evidence therefore do not necessarily conflict, the invertebrates probably having come from deposits younger than the plant-bearing beds. If it should be shown that the plant-bearing and invertebrate-bearing concretions were derived from different beds in the same formation, the evidence of age afforded by the plants would carry the greater weight, for the flora is large and well preserved as compared with the fauna.

FOSSIL PLANTS

The list of the Cretaceous fossil plants found on Marthas Vineyard given by Hollick is reproduced below. (See Plate **21**.) A list is also published by Berry,[1] but this list includes also plants from Long Island and does not give localities. So far as is known to the writer, only one addition has been made to Hollick's list since it was published—*Prepinus viticetensis* sp. nov., described by Jeffrey in 1910.[2]

Plants described by Hollick

The plants named in the following list are described by Hollick:[3]

Gleichenia protogaea Deb. and Etts.?
Thyrsopteris grevilloides (Heer)
**Onoclea inquirenda* (Hollick)
**Marsilea Andersoni* Hollick
Sagenopteris variabilis (Vel.) Vel.?
Podozamites sp.

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[1] Berry, E. W., *op. cit.*, pp. 615–618.

[2] Jeffrey, E. C., A new *Prepinus* from Marthas Vineyard, Proc. Boston Soc. Nat. Hist., **34**, No. 10, pp. 333–338 1910.

[3] Hollick, Arthur,, U. S. Geol. Survey Mon. 50, 1906.

Czekanowskia dichotoma (Heer) Heer?
Baiera grandis Heer?
Dammara borealis Heer
Pinus sp.
Cunninghamites elegans (Corda) Endl.
Sequoia ambigua Heer
Sequoia Reichenbachi (Gein.) Heer
Sequoia fastigiata (Sternb.) Heer?
Sequoia gracilis Heer?
Cone of _Sequoia concinna_ Heer
Widdringtonites Reichii (Etts.) Heer
Widdringtonites subtilis Heer
*_Widdringtonites fasciculatus_ n. sp.
Frenelopsis Hoheneggeri (Etts.) Schenk?
Juniperus hypnoides Heer
Cone scale of a conifer?
Typha sp.
Poacites sp.
Populus stygia Heer?
Aments of _Populus_ sp.
Salix membranacea Newb.
Salix Meeki Newb.
Salix proteaefolia lanceolata Lesq.
Salix proteaefolia linearifolia Lesq.?
Cone of _Sequoia_ sp.
Ament of _Myrica_ sp.
Juglans arctica Heer
Juglans crassipes Heer
*_Juglans elongata_ n. sp.
Quercus sp.
*_Planera betuloides_ n. sp.
Ficus myricoides Hollick
Ficus atavina Heer
Ficus Krausiana Heer
*_Ficus sapindifolia_ Hollick
Proteoides daphnogenoides Heer
Dryandroides quercinea Vel.
Banksites saportanus Vel.
Nelumbo Kempii (Hollick) Hollick
Menispermites acutilobus Lesq.?
Cocculus cinnamomeus Vel.
*_Cocculites imperfectus_ n. sp.
*_Cocculites inquirendus_ n. sp.
Magnolia speciosa Heer
Magnolia tenuifolia Lesq.
Magnolia pseudoacuminata Lesq.
Magnolia amplifolia Heer
Magnolia Lacoeana Lesq.
Magnolia auriculata Newb.
*_Liriodendron attenuatum_ n. sp.
Liriodendropsis angustifolia Newb.
Liriodendropsis constricta (Ward) var.
Liriodendropsis simplex (Newb.) Newb.
*_Liriodendropsis spectabilis_ n. sp.
*_Cuatteria cretacea_ n. sp.
Cinnamomum Heerii Lesq.?
Cinnamomum sp.
Persea Leconteana (Lesq.) Lesq.
*_Nectandra imperfecta_ n. sp.
Sassafras acutilobum Lesq.
*_Sassafras angustilobum_ n. sp.
Sassafras cretaceum Newb.?
Sassafras hastatum Newb.?
Malapoenna sp.
Laurus nebrascensis (Lesq.) Lesq.
Laurus teliformis Lesq.
*_Amelanchier Whitei_ n. sp.
Hymenaea dakotana Lesq.
Hymenaea primigenia Sap.
Cassia sp.
Colutea primordialis Heer
*_Dalbergia minor_ n. sp.
*_Dalbergia irregularis_ n. sp.
Leguminosites coronilloides Heer
Leguminosites convolutus Lesq.?
Ilex papillosa Lesq.
Celastrophyllum grandifolium Newb.?
*_Gyminda primordialis_ n. sp.
*_Elaeodendron strictum_ n. sp.
Fruit of _Acer_ sp.
Paliurus ovalis Dawson
Zizyphus grönlandicus Heer
*_Ceanothus constrictus_ n. sp.
*_Sterculia pre-labrusca_ n. sp.
Sterculia Snowii Lesq.
Sterculia sp.
Eucalyptus? angustifolia Newb.
Eucalyptus Geinitzi (Heer) Heer
Eucalyptus Schübleri (Heer)? n. comb.
*_Eucalyptus latifolia_ n. sp.
*_Hedera simplex_ n. sp.
Aralia grönlandica Heer
Aralia ravniana Heer
Aralia coriacea Vel.
Panax cretacea Heer
Andromeda Parlatorii Heer
Myrsine borealis Heer
Diospyros primaeva Heer

Diospyros apiculata Lesq.?
Diospyros provecta Vel.
*_Periploca cretacea_ n. sp.
Premnophyllum trigonum Vel.
Williamsonia problematica (Newb.) Ward
*_Strobilites perplexus_ n. sp.
Tricarpellites striatus Newb.
*_Tricalycites major Hollick_
Tricalycites papyraceus Newb.
*_Calycites obovatus_ n. sp.
Carpolithus floribundus Newb.
Carpolithus hirsutus Newb.
Carpolithus sp.

REPORT ON UPPER CRETACEOUS FLORA OF MARTHAS VINEYARD

By Edward W. Berry

The Upper Cretaceous flora of Marthas Vineyard comprises 117 recorded species, which were found in material collected at Chappaquiddick, Nashaquitsa, and Gay Head, most of it at Gay Head. This flora has been elaborated by David White and Arthur Hollick. Hollick considers it the equivalent of that of the Raritan formation of New Jersey, but it is obviously younger, being equivalent to that of the Magothy formation.

Fifteen of the species are confined to Marthas Vineyard. Of those discovered elsewhere 67 are not found in the Raritan, and of the 35 forms in the Raritan 29 are common to the overlying Magothy, leaving but 6 forms that are peculiar to the Raritan, and all these are vague or unique (_Carpolithus_, _Williamsonia_, _Tricarpellites_, _Tricalycites_). Nearly all of the plants found on Marthas Vineyard that also occur elsewhere are common to the Magothy of New Jersey or Maryland or to post-Raritan formations at other places. Thus 44 occur in the Magothy and 20 are peculiar to Marthas Vineyard and the known Magothy, so that I have no hesitation in correlating the leaf-bearing Cretaceous plants of Marthas Vineyard with those of the Magothy formation.[1]

Tertiary System

By J. B. Woodworth

ABSENCE OF EARLY TERTIARY FORMATIONS

No deposits of either Eocene or Oligocene age have been found in place on Marthas Vineyard. Some fragments of fossiliferous sandstone found in the surface drift on Chappaquiddick Island were referred to the Eocene epoch by Mr. Thomas C. Brown in 1905, but the position of the rock from which these fragments were derived has not been determined. The direction of glacial flowage in the district would lead one to look for this sandstone in place along a line extending northeastward across Cape Cod past Barnstable and thence north and north by west under the water of Massachusetts Bay. Fragments of similar rock, a ferruginous sandstone or mudstone carrying casts of marine mollusks, are scattered over the surface of the island as far west as Gay Head, but these fragments contain Upper Cretaceous fossils.

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[1] Berry, E. W., Jour. Geology, **23**, pp. 608-618, 1915.

MIOCENE SERIES

Miocene fossils were seen in the first half of the nineteenth century in the cliffs at Gay Head, and for a time not only all the folded and contorted beds there but all the deposits on the island under the surface moraines were regarded as Miocene. Later scrutiny of the beds and the discovery in them of additional fossils, however, led to the restriction of the Miocene deposits to not more than two distinct beds in the Gay Head cliffs, and one of these beds (the osseous conglomerate), which contains Miocene fossils, is, for reasons already stated in this report, now referred to the very dawn of the Pleistocene epoch, a period before the advent of the glaciers. The Miocene series, therefore, is here represented by a single deposit, long known as the "greensand bed," which in places at Gay Head appears to be underlain by a deep-blue clay that also contains Miocene fossils.

THE GREENSAND

Character

The Miocene greensand is a greenish to brownish bed, in places clayey, composed largely of the small nodular remains of foraminifers, many of them of genera peculiar to the Cretaceous deposits of the coastal plain of Maryland. At some places the bed looks so much like certain beds of Cretaceous greensand of the Atlantic coast that some geologists have suggested that it may have been redeposited on Marthas Vineyard from a Cretaceous formation, but no sections thus far exposed in the island have given reason to believe that greensand was laid down in this area during Upper Cretaceous time. Moreover, the occurrence of casts of Miocene mollusks in the greensand bed, many of them in the attitude of growth, and the absence of any Cretaceous admixture of such fossils make it reasonable to suppose that the greensand is a local deposit, formed when the conditions favored the growth of foraminifers and the accumulation of their remains on the sea floor.

Oxidation

The normal color of the greensand bed in this area is a peculiar shade of green, which is invariable in the lower part of the bed, whether that part has been inverted by folding or not. The upper part of the bed, and in places the whole of it, has been made rusty red by the oxidation of the iron in the original glauconite of the foraminiferal nodules, and at many places in the Gay Head cliffs the so-called greensand is therefore a rusty red bed.

THICKNESS

The thickness of the greensand bed varies greatly in its exposure in the Gay Head cliffs east of the lighthouse, to which part of the island it is apparently limited. The bed is at few places more than 3 or 4 feet thick, but in certain folds it appears to be as much as 10 feet thick.

A small bed of greensand carrying much clay was found in a vertical position in the Nashaquitsa cliffs in 1899, about in the position of the Pleistocene beds, in contact with the Cretaceous deposits exposed there. This bed disappeared in the retreat of the cliffs several years ago.

UNCOMFORMABLE CONTACT WITH CRETACEOUS CLAY

The greensand rests with sharp unconformity upon the underlying Upper Cretaceous clay, though the beds are so greatly disturbed that a change of dip in the two formations is not recognizable. Fair exposures of the greensand beds in the Gay Head cliffs may usually be seen at stations 13, 16, 17, 19, 20, 21, 23, 24, and 28, on a chart of Gay Head cliffs accompanying a paper by J. B. Woodworth.[1]

FOSSILS

The greensand in the Gay Head cliffs has yielded several fossils, most abundantly casts of the clam-like form *Macoma lyelli* Dall. Many of these casts are in the attitude of growth in the foraminiferal mud. Casts of gastropods, the remains of at least two species of crabs, and the teeth of sharks are also occasionally found, along with the vertebrae of cetacea, chiefly whales. The vertebrate bones include the tooth of a walrus, possibly that of a seal, and among land animals that of a small rhinoceros.

The assemblage of fossils found in the greensand suggests a division in the history of the greensand bed into an earlier period, in which the greensand was laid down, possibly in deep water, and a later period, when shallow-water mollusks like *Macoma* and *Panope* bored into the foraminiferal mud. The bones of whales found at or near the base of the bed may indicate a still earlier period of shallow water. Certain cobbles or rolled stones, the largest 5 or 6 inches in diameter, composed of a quartz-pebble conglomerate, found at or near the base of the bed in 1889, appear to have been derived from some part of the underlying Cretaceous deposits rather than from the breaking up of the osseous conglomerate, as was then thought. In the course of the reëxamination of the cliffs in 1915–16 no such cobbles were found in the greensand bed.

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[1] Uncomformities of Marthas Vineyard and Block Island, Bull. Geol. Soc. Am., **8**, 1896, Plate 16, p. 197.

In places at Gay Head the greensand appears to be underlain by a deep-blue clay containing few foraminifera but the same assemblage of fossils. It was in such a bed that the tooth of a rhinoceros was found.

From such reconstruction of the highly distorted beds as can now be made, it would seem that the Miocene sea swept over the site of the island while the beds of Cretaceous clay and sand formed an undisturbed eastward extension of the coastal plain like that still remaining southwest of Staten Island, and that the water gradually deepened until the shore line, advancing across the lowland of southeastern Massachusetts and Rhode Island, lay so far from the present shore line that little or no sand and mud reached the site of Marthas Vineyard. During this stage, in water that may not have been more than 50 or 60 feet deep, the deposits of foraminifers were laid down by the life and death of these organisms in that part of the sea. The story of the retreat of the sea in the succeeding Pliocene epoch belongs to the account of the immediately overlying fossiliferous sand.

PLIOCENE SERIES

A deposit of sand carrying Pliocene fossils was found in 1899, faulted down as a block less than 2 feet thick and having an exposure on the cliffs about 6 feet long, in the upper surface of the Miocene greensand bed near the north end of the cliff, at an elevation of 80 feet. This remnant of a marine deposit that was apparently widely extended is the only known Pliocene bed east of Southampton, Long Island. If the interpretation here made is correct, the Aquinnah or osseous conglomerate is a land deposit laid down at the very dawn of the Pleistocene epoch, before the ice sheets reached the south shore of New England.

AQUINNAH CONGLOMERATE (EARLIEST PLEISTOCENE)

In the part of the Gay Head cliffs that is described by Hitchcock as the ''quadrangular fold,'' between stations 30 and 36, there is exposed above the white Cretaceous beds a bed of conglomerate, from 12 to 18 inches thick, made up of rounded quartz pebbles; black and grayish, well rounded, smooth, and in places highly polished chert pebbles; and an admixture of cetacean bones, shark teeth, and, occasionally, a cast of a mollusk. This bed has yielded also a bone of an early type of American camel and the astragalus of a highly developed Pleistocene horse, which were dug out of the bed some years ago by me (Plate 22). The cetacean bones, the teeth of sharks, and the molluscan remains, all in the condition of pebbles swept together by the action of water, have by all previous observers been referred to the Miocene. Some of the chert pebbles carry fossils now known to be of Helderberg (Lower Devonian) age. Until the Pliocene and early Pleistocene fossils were discovered it seemed likely that the bed of conglomerate was a beach or shoal deposit that had been rudely assembled by currents or waves. It now seems more reasonable, however, to regard the bed as a deposit laid down in a shallow stream on the border of the coastal plain, in which the coarser debris, of mineral and organic origin, washed out of neighboring banks from Cretaceous and Miocene beds, perhaps from the greensand bed, accumulated in the open air on the surface of eroded Cretaceous sand and clay. This interpretation accounts for the local occurrence of the bed, which has not been recognized, either as an unbroken deposit or as rolled fragments, outside of Gay Head and the western part of Marthas Vineyard. Both north and south of the exposure mentioned, rolled fragments of this bed occur on the unconformable surface separating the Cretaceous deposits from the older Pleistocene boulder beds and gravel deposits. Some cobbles, a few inches in diameter, have been found at the same geological horizon near Peaked Hill and on the south slope of the island near that hill as far east as a roadside ravine at the east end of the flattish hill on the north side of Chilmark Pond, a hill that affords an excellent view of the south shore.

The entire absence of pebbles of granite, gneiss, and other feldspar-bearing rocks in this conglomerate indicates its derivation from wash of the underlying Cretaceous and Tertiary deposits at a time when the beds of the Coastal Plain stretched northward over the area of the Sound and Buzzards Bay. This conception presents a picture of the dawn of Pleistocene time, when the probably drier climate of the Pliocene epoch, indicated by the remains of a camel, had given way to the cooler and moister Pleistocene climate, before the first ice sheet had driven the native horse beyond the limits of glaciated New England.

Quaternary System

By Edward Wigglesworth

PLEISTOCENE SERIES

The remarkable abundance and variety of the Pleistocene deposits on Marthas Vineyard reveal much more Pleistocene history than can be deciphered at other places in New England, where the Wisconsin deposits dominate all other glacial phenomena. On Marthas Vineyard the reverse is the rule, the Wisconsin deposits form only an insignificant part of the Pleistocene beds, and only the earlier ice of Wisconsin time extended so far south. The series is very nearly the same as that on Long Island, New York, but no exact correlations of the earliest deposits can be made. These deposits and their probable correlation are more fully considered by Professor Woodworth in Part I of this report. The series, as made out, is as follows: —

- Wisconsin moraine and outwash
- Manhassett formation
  - Hempstead gravel member
  - Montauk till member
  - Herod gravel member
- Jacob sand
- Gardiners clay
- Jameco formation
  - Moshup till member; at Nashaquitsa cliffs
  - Coarse gravel of typical Jameco type; at Gay Head and Nashaquitsa cliffs
  - Ferruginous boulder bed; at Gay Head
- Mannetto formation: at Gay Head cliffs
- Weyquosque formation: at Gay Head and Nashaquitsa cliffs
- Dukes boulder bed: at Gay Head cliffs
- Aquinnah conglomerate: at Gay Head cliffs

EARLY PLEISTOCENE DEPOSITS (PRE-GARDINERS FORMATIONS)

The lowest formations of the Pleistocene series, including all those laid down before the deposition of the Gardiners clay, are clearly exposed in only two small outcrops, one in the Gay Head cliffs, the other in the Nashaquitsa cliffs. Small exposures of what are thought to be the same beds occur at five other places, notably at Norton Point. Only in the two cliff sections are the beds well enough exposed to justify an attempt to interpret their relations, but the exposures are so small and so obscure that the interpretation made can be regarded as only tentative. The interpretation proposed does not agree with that proposed for the deposits on Long Island that preceded the Jameco, as described by Fuller,[1] which consist solely of a gravel called the Mannetto gravel.

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[1] Fuller, M. L., Geology of Long Island, New York, U. S. Geol. Surv. Prof. Paper 82, pp. 80–92, 1914.

This deposit, which consists of rounded pebbles of quartz in a quartz matrix, is the only one in the Pleistocene series that precedes the Jameco, from which it is separated by a marked unconformity representing a long period of erosion. According to Fuller,[1] the Mannetto does not exist on Marthas Vineyard, having probably been removed by post-Mannetto erosion. The Jameco gravel, according to Fuller, is the oldest Pleistocene deposit on Long Island. To this deposit he assigned the well-exposed gravel that lies below the Gardiners clay in the Nashaquitsa cliffs. The present writers, however, believe that four older Pleistocene beds lie below the Jameco gravel.

Sections in Gay Head Cliffs

Aquinnah conglomerate.—In the Gay Head cliffs, directly below the lighthouse, there is a large quadrangular fold in which the lower members are beds of Upper Cretaceous sand and clay. Above these beds, according to Woodworth, there is a thin bed, formerly thought to be of Miocene age, called by Hitchcock the osseous conglomerate. The larger constituents of this bed are small, well-rounded, white quartz pebbles, chert pebbles, and cetacean bones. The bones and some shark teeth, as well as the fact that the deposit was formerly supposed to lie below undoubted Miocene greensand, led to the belief that it also was of Miocene age. Later, however, a metacarpal of a Pliocene camel and an astragalus of a Pleistocene horse were found in this bed[2] (Plate **22**). It must therefore be regarded as a Pleistocene deposit formed before the ice reached the region. The presence of Tertiary fossils in the bed is due to the erosion and redeposition of preëxisting deposits. Woodworth has given to this osseous conglomerate the name Aquinnah, the Indian name for Gay Head.

Dukes boulder bed.—Above the Aquinnah conglomerate in the Gay Head cliffs there is a remarkable bed of boulders, entirely free from clay, which was described by Woodworth in 1897,[3] and by Shaler in 1889. This bed at one time contained boulders as much as 8 feet long, weighing about 4 tons. The boulder bed is composed of granite, diorite, and gneiss from the mainland and includes also a small boulder of peridotite from Iron Mine Hill, in Cumberland, Rhode Island, 60 miles away. The bed is locally cemented by limonite and contains pebbles of Cretaceous sand and clay. Many of the boulders are much decayed and can be broken up readily with a hammer. The nature of this bed, and especially the glacial striae on one of the boulders, shows that it was formed by the action of ice, and it is therefore regarded as the product of an early ice sheet at a time not far from the beginning of the Pleistocene epoch. To this bed Woodworth has here given the name Dukes boulder bed.

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[1] *Op. cit.*, pp. 219-220.

[2] Woodworth, J. B., Glacial origin of older Pleistocene in Gay Head cliffs, with a note on fossil horse of that section, Bull. Geol. Soc. Am., **11**, pp. 455-460, 1900.

[3] Woodworth, J. B., Unconformities of Marthas Vineyard and of Block Island, Bull. Geol. Soc. Am., **8**, p. 205, 1897.

Mannetto formation.—Immediately above the Dukes boulder bed in the quadrangular fold, directly below the lighthouse, is a bed of stony blue clay till not noted in previous reports and first seen in 1916. This bed is exposed also at another place in these cliffs, south of the quadrangular fold. This material is clearly an ice-laid till, and it differs from the underlying boulder bed in containing no boulders and some clay. It was probably formed by a later ice advance than that which deposited the boulder bed, and it is here assigned to the Mannetto stage.

Overlying the stony blue clay is a bed of gravel somewhat thicker than either of the lower beds. This is the uppermost member that is involved in the quadrangular fold, and, with the exception of a thin Wisconsin coating, it forms the highest part of the cliffs. Whether this gravel belongs to the Jameco or to the Mannetto stage is not certain, but it is here assigned to the Mannetto because the Jameco deposits succeeded the folding and erosion.

Evidence of pre-Gardiners age of deposits.—The beds exposed in this part of the Gay Head cliffs are all older than the Gardiners clay, a fact shown by the relations between the older beds and the Gardiners clay where the clay is exposed at the north end of the cliffs. In the Gay Head section the Cretaceous, Tertiary, and oldest Pleistocene beds are all closely folded and are overlain uncomformably by a thin veneer of Wisconsin drift except at the end of the section. At the north end of the section the Gardiners clay is exposed, lapping up unconformably on the underlying beds, as if these beds had formed an island at the time the Gardiners was laid down. The Gardiners clay has been slightly folded, but much less than the older beds. Exposures at Nashaquitsa cliffs and elsewhere attest this fact.

The post-Mannetto period of folding.[1]—According to earlier reports on Marthas Vineyard most of the dislocation of the beds in the Gay Head cliffs antedated the deposition of what was then known as the "Tisbury beds," on the north shore of the island. As defined, these beds included the Gardiners clay and certain younger deposits. The sections now exposed on Block Island and Marthas Vineyard indicate that most of the folding and overthrusting of the Cretaceous and Tertiary beds preceded the deposition of the Gardiners clay and the Jameco gravel or of the boulder beds at that horizon in certain sections. If the strata were distorted by pushing or dragging at the margin of an ice sheet advancing from the north, the earliest competent ice advance would have shoved the beds into a position of approximate equilibrium, so that subsequent ice advances would leave no marked signs of their work. This appears to be true, and we are therefore led to believe that the ice advance of the Jameco stage was the greatest that had taken place since the beginning of Pleistocene time, but the nature of the folding alone does not indicate that this ice advance was less vigorous than those which followed it. In the typical section of the beds that were folded and overthrust at this time, both on Block Island and Marthas Vineyard, the overthrust moved from the landward side toward the sea. The deployment to the southwest, over the Gay Head section, as compared with the overthrust to the southeast, over Marthas Vineyard east of Menemsha Creek, indicates the existence of a small lobe or tongue that pushed southward through the depression occupied by Menemsha Pond. This depression, along with the rest of the island, has been an area of deposition and erosion, but probably its original cause lies in its axial position in reference to the ice push at this time.

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[1] Note by J. B. Woodworth.

The deposition of the Gardiners clay about what appear to have been islands or shoals of Cretaceous clay has already been noted. The precise character of the topography impressed upon the coastal plain by the ice sheet is not known. Probably much of the inequality of the surface is a result of differences in the resistance of the beds to crowding and dislocation. The surface of the deformed mass was highest where the clays permitted packing, which foreshortened the section and consequently forced the moving ice to ride over the rising obstruction. Whether this action took place beneath sea level or above cannot easily be determined. The general character of the Jameco gravel suggests shallow water or the action of streams on a plain above sea level. The immediately succeeding Gardiners clay was evidently laid down during a period of submergence.

Nashaquitsa Cliffs. (Plate **23**, fig. 1)

Weyquosque formation.—At the east end of the Nashaquitsa cliffs the pre-Gardiners beds are exposed, although the complete series seen at Gay Head is not shown. The east end of these cliffs consists of Cretaceous sand and clay, against which abut the older Pleistocene beds. (Fig. 11.)

The lowest Pleistocene bed grades from brown gravel up into a dark sand, the upper part of which has a greenish cast. At its base this material consists of coarser feldspathic sand containing shark teeth, phosphatic nodules, and fragments of lignite. The organic remains appear to have been reworked and are derived entirely from Tertiary and earlier strata. The bed has been so much disturbed that it is now upturned into a nearly vertical position. This is the Weyquosque formation of Woodworth.

Note by J. B. Woodworth: In July, 1920 my attention was called to an opening in a gravel knoll on the land of Mr. Ernest Flanders, in Chilmark, about three-fourths of a mile south of the North Road and half a mile west of Menemsha Pond. This opening exposed Weyquosque gravels containing shark teeth, waterworn pieces of cetacean bone, phosphatic nodules, and some Miocene greensand, a mixture of glacial gravel and organic débris from the Aquinnah or osseous conglomerate and the Miocene greensand. The red sandy ground west of the opening and along the shore of the pond appears to be a broad outcrop of the Jacob sand. On the shore south of Mr. Arthur A. Brigham's land outcrops of the Montauk till form the higher bluffs.

Moshup till member of Jameco formation and overlying beds.—Above the lowest Pleistocene (Weyquosque) gravel, and separated from it by an unconformity, is a conspicuous bed of till containing boulders, some as much as 8 feet in diameter, embedded in a stony clay matrix. Boulders that were once a part of this bed but that fell out of it because of the removal of the matrix by the waves form a small point on the beach known as Boulder Point. The former extent of the bed is marked by a train of boulders that extends out into the water. The contact between this boulder bed and the lower Pleistocene (Weyquosque) gravel is nearly vertical, and the boulder bed itself stands in a vertical position. This bed, unlike the bed of gravel below it, contains clay and boulders. These beds therefore resemble the Pleistocene beds in Gay Head, where a bed of stony blue clay simulates a deposit of till, but the stony blue clay in the Gay Head section is regarded by Professor Woodworth as an older deposit, of Mannetto age. The stratigraphic relations here are described more fully by Professor Woodworth. The positions of the beds both in Nashaquitsa cliffs and in Gay Head indicate a vigorous ice advance before the deposition of the Gardiners clay.

Against this conspicuous boulder bed rests the Gardiners clay, but obviously not as it was originally laid down, for it is folded in small plications, which indicate that it has been thrust against the boulder bed, probably by later ice action, and possibly that which deposited the Montauk till and forced the plastic clay against this resistant bed of boulders. The typical Jameco type of gravel is not exposed here, but it may be concealed by the beach. Professor Woodworth regards the Moshup till as the correlative of at least the upper part of the Jameco gravel of Long Island.

Fig. 11— Geological section of Nashaquitsa Cliffs.

NORTON POINT

Near the northeast end of the section at Norton Point there is exposed a bed of tough, compact, stony blue clay, which underlies the Gardiners clay. This bed, which is about 10 feet thick, is exposed at the very tip of the point, where the surface of the bed has a steep shoreward dip. Its relation to the overlying beds makes it appear to have an eroded surface, on which the later deposits were laid down unconformably.

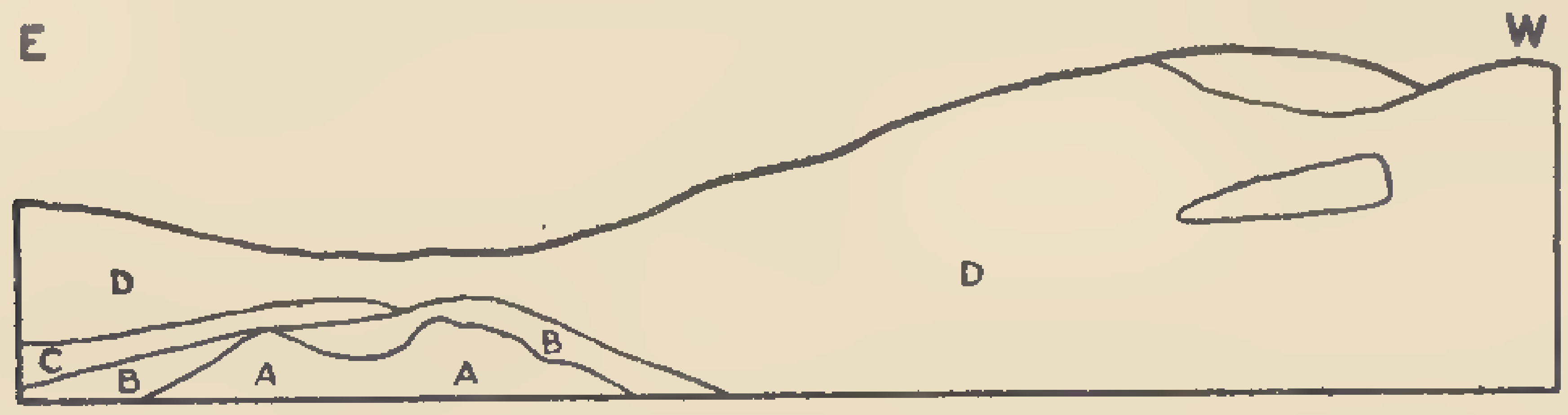

FIG. 12.— Section at Norton Point, showing old till below Gardiners clay. A, pre-Gardiners till; B, Gardiners clay; C, Jacob sand; D, Manhasset formation.

OTHER EXPOSURES

Other exposures of beds of gravel that are lithologically like the lowest Pleistocene gravel but that do not show their relations to other beds, have been found at a few places, but these beds cannot be safely employed in the interpretation of the geology. One of these beds, which is seen in a cut on the state road near the top of Longview Hill, in Chilmark, consists of bedded gravel similar to that in the anticline at Nashaquitsa cliffs. Another is in a shallow gravel pit a few yards north of the state road, due north of the west end of Chilmark Pond, where the gravel is like that in the bed just described. Another bed is in the Indian Hill region, on the south side of the 275-foot hill. Here a gravel pit discloses greenish sand such as that at the boulder point on Nashaquitsa cliffs. Still another bed is in the cliffs just west of the mouth of Roaring Brook where some gravel may be seen below the Gardiners clay. The section here is so much disturbed, however, that the stratigraphic position of the bed cannot be determined exactly.

GARDINERS CLAY

(See Plate **23**)

NAME

The Gardiners clay was named from Gardiners Island, which lies between the north and south flukes at the east end of Long Island. On this island several beds of clay that include some sand are well exposed at a number of places.[1]

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[1] Fuller, M. L., *op. cit.*, p. 92.

CHARACTER

On Marthas Vineyard the Gardiners clay consists entirely of fine, grayish-black silt or clay, which in places has a bluish tint, giving rise to the local name of "blue clay." (Plate **23**, fig. 2). On this island it lacks inter-bedded sand except near its top, where it grades into the Jacob sand. Its color is probably due in part to organic matter, for fragments of lignite have been found in it at several places. These fragments appear to be considerably waterworn. When wet the clay is very plastic; when dry it may be reduced to a light-colored powder by slight rubbing or pressure.

THICKNESS

The thickness of the Gardiners clay on Marthas Vineyard cannot be determined accurately because it has been greatly disturbed, but it is probably not more than 35 feet thick, much thinner than it is near Brooklyn, on Long Island, where, according to Fuller,[1] its aggregate thickness (including layers of sand and gravel) is 150 feet. Wherever its thickness on Martha's Vineyard is greater than about 30 feet, it has been highly contorted.

SOURCE OF MATERIAL

Fuller holds that the Gardiners clay is of interglacial origin because the marine fossils it contains indicate a moderate climate and its thickness indicates a long period of deposition. On Marthas Vineyard only one fossil has been found in it and its thickness is much less than that on Long Island. On Cape Cod Woodworth has found large lenses of clay of possible Gardiners age, a fact that does not indicate extensive interglacial deposition.

The evidence obtainable on Marthas Vineyard and elsewhere therefore shows that the Gardiners clay along the south shore is of marine origin. Whether the clay is of interglacial or glacial origin cannot be determined, but it is not necessarily interglacial, for all the conditions requisite to its deposition would have existed when the ice front stood some distance back of this area. The distribution of the clay and its marine origin indicate that the Gardiners stage was a time during which the main shore line lay somewhat back of the area in which clay was deposited. On this shore line the waves and currents were working on deposits left by the retreat of the ice and were carrying away the finer part of these deposits from the shore and depositing it as clay. Thus the Gardiners clay is considered a glacial or an interglacial marine deposit, which is composed largely of reworked glacial and perhaps of some reworked Cretaceous material, laid down at a time of considerable submergence.

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[1] Fuller, M. L., *op. cit.*, p. 93.

RELATION TO OLDER DEPOSITS

The Gardiners clay probably rests conformably on the gravel near the middle of the Nashaquitsa cliffs section, but unconformably on the deposits at the east end of Nashaquitsa cliffs and at Norton Point. At Gay Head cliffs the Gardiners clay does not form a part of the section, except at the north end, but it is found on the shore east of the cliffs, where it dips away from the cliffs. It therefore seems that the Gardiners clay was deposited around the area now occupied by the cliffs at a time when they probably formed an island. This same relation is seen at Norton Point. Thus the clay lies conformably upon earlier deposits at some places and unconformably at other places. This fact seems to show that when the deposition of the Gardiners clay began the region was only partly submerged, and that the water in which the clay was deposited was not very deep.

The beds of Gardiners clay have, of course, been considerably distorted by later advances of the ice and the evidence shown by their relations to older deposits is therefore not altogether reliable. At the boulder point on Nashaquitsa cliffs the clay has been thrust against the older beds, and at many places it has been overthrust on itself, or even on later beds.

STRUCTURE

At many places the Gardiners clay shows a laminated structure, due to its original bedding. The laminae average about half an inch in thickness. Without these laminae it would be a dense, homogeneous clay throughout, except in some places near the top, where it is interbedded with layers of fine sand. The larger structural features of the Gardiners clay are folds and overthrusts. At some places the clay bed is nearly horizontal; at others it has been closely folded; and between these two extremes there are all gradations. At some places where the clay has been subjected to lateral pressure the beds have been thickened and thrown into small folds. Small faults that have slickensided faces have also been seen in the clay, but these are probably due to landslips. At some places where another formation has been pushed over the clay both beds have been dragged. Where a large exposed surface of the clay is alternately wet and dry, parting planes have been formed both on the bedding planes and at right angles to them.

The folding in this bed is in places greatest along the northwest shore, where the strike is generally northeastward. The folding occurs where the action of the ice would naturally be strongest. It is not easy to explain why overthrusting without close folding took place farther southeast of the strongly folded area. Possibly the ice cover here was thin and allowed the whole bed to be pushed southeastward as a more or less rigid layer. The fact that the Gardiners clay has been overthrust on itself tends to give this theory more weight than the theory that the low, gentle warping of the clay bed is due to the weight of the ice, although such action may have occurred elsewhere, or perhaps even here to some extent, for under sufficient pressure this clay would doubtless have been compressed and otherwise molded.

Date of the Folding of the Gardiners Clay

The folding that the Gardiners clay has undergone was caused by the Montauk ice sheet. It is most pronounced along the northwest coast, where the ice probably actually pushed and shoved both the Gardiners clay and the Jacob sand. The distortion of the clay elsewhere is such as would be caused by a heavy mass of overriding ice. The clay, being plastic, would be squeezed out where the pressure was greatest and would accumulate where the pressure was least. The deformation was not due to Wisconsin ice, for the pre-Wisconsin topography of the Vineyard interval was not perceptibly altered by this final glaciation.

Conditions during Deposition

The conditions under which the Gardiners clay was deposited have already been suggested. The nature of the material alone indicates that it was deposited in water in an area that lay rather far from the shore, for it includes no coarse material. The main evidence of its mode of deposition, however, lies in its fossils. These are marine forms which, according to the senior author, lived when the clay was being deposited, for they were found in the position of growth and showed no signs of transportation. Submergence and the active work of wave and current were therefore necessary to supply and transport the material. It is possible that silt-laden rivers may have supplied some of the fine sediment.

Distribution

The Gardiners clay is found only in the western part of the area. It probably does not underlie the whole area, as do the Cretaceous deposits, and it is doubtless absent wherever the earlier deposits rise as high as 100 feet. Sections at Gay Head and Norton Point indicate that the clay was deposited around remnants of the earlier Pleistocene and Cretaceous beds. The clay is found under the Vineyard Sound margin of the western area and is exposed at many places along the shore. Later action of the ice has undoubtedly removed the clay from some places where it was originally deposited and has thickened it in others, but as it was deposited on the lowlands of that time it was to some extent protected by the remnants of older formations that stood at a higher level.

Along the southwestern margin of the western area the clay is not so well exposed, except in Nashaquitsa cliffs. Northeast of these cliffs the outwash gravel and morainal material cover nearly all places where the clay might be expected. However, the clay probably lies along the southeast side of the morainal region and flanks the earlier deposits there in much the same way as it does along the northwest side.

Outcrops

In Gay Head cliffs the Gardiners clay is conspicuously absent except at their north end. The only other clear exposure in the town of Gay Head is along the west shore of Menemsha Pond, where the clay is seen at the base of low cliffs, slightly above the level of high tide. Other doubtful exposures can be seen in the eastern part of the town, along the state road.

The clay is found at places along the south shore of Menemsha Pond. The exposures are the same as those along the west shore. In both localities the clay is overlain by the Manhasset formation.

In an anticline near the center of the section seen in the cliffs at Squibnocket the Gardiners clay is exposed for a short distance below the Manhasset.

The Gardiners clay is one of the most conspicuous beds in Nashaquitsa cliffs. It occupies a large part of the section, which affords the best exposure of this formation on the island, for both the top and the bottom of the bed are seen, as well as its folded and overthrust structure and its local thickening due to compression. (See Fig. 11.) West of these cliffs the clay apparently lies below sea level, but here it rises as high as 100 feet above the beach and shows several gentle folds and some overthrusts. One long section of the cliffs is made up entirely of Gardiners clay, but farther east the bed is abruptly broken off and the remainder of the section, except two short stretches, reveals only older beds.

Along the shore of Vineyard Sound, between Menemsha Creek and Norton Point, there are several exposures of Gardiners clay. The first of these, beginning at the southwest end, occurs west of Prospect Hill. Here the clay is gently folded and is overlain by the Jacob sand and Manhasset formation. About half a mile beyond this place the Gardiners clay is exposed in the face of the cliff as if it were nearly horizontal, but in a gully that runs at right angles to the shore it has the form of a close anticline, the upper part of which is exposed along the face of the cliff. A third exposure of the clay is seen immediately west of the mouth of Roaring Brook. Here it has been so much compressed that it is abnormally thick and full of small plications. The clay here was once worked for making bricks, and the remains of the old brickyard are still seen at the mouth of the brook. The clay is here overlain by a thick bed of Manhasset gravel. In one of the gullies at this locality a bed of gravel lies below the Gardiners clay. The clay here has probably been overthrust on this bed, which resembles the Manhasset and not the pre-Gardiners beds.

East of the mouth of Roaring Brook the Gardiners clay is exposed in the cliffs more extensively than elsewhere along this coast. It is considerably disturbed (see Figure 13) and is overlain by the Jacob sand and the Manhasset formation. Northeast of this locality, as far as the section between Lambert's Cove and Norton Point, the Gardiners clay is not exposed, and only a small amount of clay can be seen at either of these two places. At Norton Point the clay overlies unconformably a bed of old till. The relation between these two beds at Norton Point is one of the best evidences as to the age of the till. (See fig. 12.) The overlying beds are again the Jacob sand and the Manhasset formation.

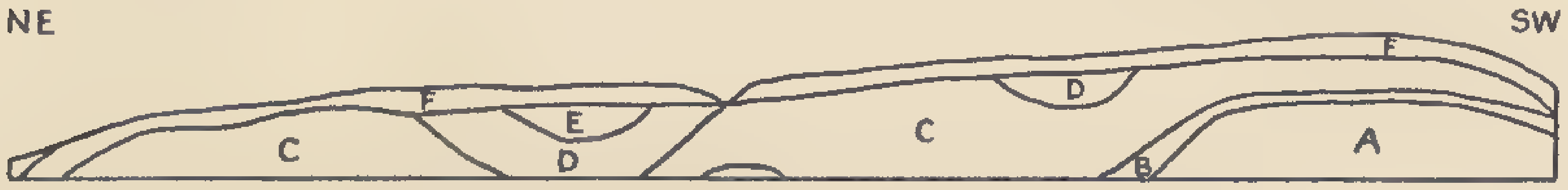

FIG. 13. — Section on the shore northeast of Roaring Brook. A, Gardiners clay; B, Jacob sand; C, Herod gravel; D, Montauk till; E, Hempstead gravel; F, Wisconsin till. The Herod, Montauk, and Hempstead are members of the Manhasset formation.

About a quarter of a mile southwest of the small long pond between Chappaquonsett and James ponds, and again southeast of it, there are small old pits from which clay was once dug. This clay is said to have burned red and probably the Gardiners is a red-burning clay. The place where it occurs is not one where it would be expected, and the deposit stands at a much higher elevation than any other known bed of the Gardiners clay.

FORM OF SURFACE

Large lenses of the Gardiners clay have been variously distorted by the action of the Montauk ice, so that their surfaces vary from nearly flat to sharply ridged, the ridges having been caused by anticlinal folding. The amount of distortion, and therefore the irregularity of the surface, varies, for at some places the clay was exposed to the full force of the ice action and at others it was protected by remnants of older and more resistant beds. The weight of the overriding ice also modified the surface, partly by abrasion, but even more because the plasticity of the clay allowed it to be flattened out where the pressure of the overlying ice was greatest. In places a whole mass of the clay was evidently pushed or dragged from its original position over itself or over other beds. Thus at some places the Gardiners clay presents a level, undisturbed surface and is overlain by the later Jacob sand, and at others its surface is a well-defined ridge, which may or may not include the Jacob sand. At still other places the surface was kneaded into undulations by the overriding ice and the Gardiners clay is usually accompanied by the conformably overlying Jacob sand. At still other places the surface was originally broken, but its irregularities were smoothed off by the action of the ice.

Fossils and Age

The Gardiners clay is of Pleistocene age, a fact shown by its relation to earlier deposits of unmistakable glacial origin at the north end of Gay Head cliffs, at Nashaquitsa cliffs, and at Norton Point. This clay also overlies earlier Pleistocene deposits on Long Island. As it was laid down later than two earlier beds, one of gravel and the other of till, and probably later even than a second bed of gravel, it evidently does not belong in the earliest Pleistocene. The Gardiners clay overlies these beds unconformably, so that it was probably laid down after a period of erosion in addition to periods of deposition.

Since the Gardiners clay was deposited, the Jacob sand, the Manhasset formation, and the Wisconsin moraine and outwash have all been formed, and there has been also the Vineyard period of erosion. Thus the Gardiners clay, according to the stratigraphic evidence in this region, appears to be of about mid-Pleistocene age.

No fossils have been found by the present writer in the Gardiners clay in this area. One is mentioned by Dall,[1] — *Modiolaria nigra* (now known as *Musculus nigra*), which he stated had been found at "Chilmark, in gray clay." Professor Woodworth has told the writer that this fossil came from the Gardiners clay. *Musculus* (*Modiolaria*) *nigra*, a marine form, is clearly Pleistocene and Recent. Fossils consisting chiefly of marine shells have been found in the Gardiners clay on Long Island.

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[1] Dall, W. H., Notes on the Miocene and Pliocene of Gay Head, Marthas Vineyard, Mass., etc., Am. Jour. Sci., 3d ser., **48**, p. 297, 1894.

Stratigraphic evidence shows that the Gardiners clay is of the same age as the similar clay on Long Island, Gardiners Island, Block Island, and Nantucket. It cannot be correlated certainly with the Pleistocene deposits of the Mississippi Valley, although Fuller,[1] who considered it an interglacial formation, has suggested with much caution that it may be assigned to the Yarmouth interglacial stage.

JACOB SAND

Name

The name Jacob sand, according to Fuller,[2] its author, is derived "from Jacob Hill, a high point on the north shore of Long Island, 8 miles northeast of Riverhead, near which the formation is well exposed." On Long Island the Gardiners clay grades upward through interlaminated clay and sand into the fine silty sand of the Jacob formation, whose deposition followed that of the Gardiners clay without a break. Nevertheless, this sand and clay show sufficient lithologic difference from the Jacob formation to permit their recognition throughout Long Island and the islands farther east. The position and character of this sand on Marthas Vineyard establish its identity with that on Long Island.

Character

The Jacob formation is composed of extremely fine sand, made up of grains of quartz and of some flakes of muscovite and grains of dark minerals. This silty sand is somewhat plastic when wet and thus resembles the Gardiners clay. In color the Jacob sand is usually a light gray, but at some places it shows yellowish shades and grades into a buff sand. It is generally well stratified. At some places the sand contains interbedded layers of clay; at other places it contains beds of coarser sand. The Jacob sand is rarely over 12 or 15 feet thick, but as it is transitional from the Gardiners clay its limits are not everywhere easily established. Wherever it is seen it rests on the Gardiners clay, whose irregularities and distortions it follows closely.

Source of Material

A slight change of conditions from those that prevailed when the Gardiners clay was formed would cause a gradual change from the deposition of clay to the deposition of the fine sand of the Jacob formation. Fuller [3] suggests that the change might be due to any one of three causes: a change in level, a change in the direction and strength of the currents, or the advent in the region of the finer material from the outwash of an advancing ice sheet, or to any combination of the three. The sequence of the deposits is suggestive. The Jacob sand overlies clay and is overlain by the lower coarser gravel, and that by the Montauk till of the Manhasset formation, a sequence suggesting that the material was laid down by an advancing ice sheet that deposited it more rapidly as it came nearer to this area.

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[1] Fuller, M. L., The geology of Long Island, N. Y., U. S. Geol. Survey Prof. Paper 82, p. 106, 1914.

[2] *Op. cit.*, p. 107.

[3] *Op. cit.*, p. 107.

Structure

The Jacob sand has suffered the same deformation as the Gardiners clay and the deformation took place under the same conditions except, that as the sand lay above the clay, it was subject to greater erosion by the overriding ice sheet. This fact explains why the Jacob sand is absent in places above the Gardiners clay, which is thus left directly in contact with one of the members of the Manhasset formation. As the Jacob sand is fine grained and is plastic when wet, and as it overlies a bed whose upper surface was very unctuous and slippery, it acted exactly as part of the underlying clay. At a few places where it was more directly exposed to the ice, the sand has been more deformed than the clay.

Conditions during Deposition

The conditions that prevailed during the deposition of the Jacob sand were similar to those that prevailed during the deposition of the Gardiners clay, except that deposition was more rapid, probably because of the advance of the ice sheet, and that the material laid down was slightly coarser. In addition, there must have been a slight progressive elevation of the area, so that in the period during which the deposit was laid down the water was somewhat shallower than it was in the preceding period. In the main, the period of deposition of the Jacob sand was a time in which the greater part of the area was under water.

Distribution and Exposures

The Jacob sand is everywhere underlain by the Gardiners clay, and its distribution is therefore practically the same as that of the Gardiners clay. At some places, however, the Gardiners clay is not overlain by the Jacob sand, which had been removed by erosion, largely by the Montauk ice. Thus, although the distribution of the Jacob sand is nearly the same as that of the Gardiners clay, its area is somewhat smaller.

The Jacob sand is therefore exposed in the same places as the Gardiners clay, namely, in the Squibnocket and Nashaquitsa cliffs, along the shore of Menemsha Pond, and along the shore of Vineyard Sound. In the central part of the Nashaquitsa cliffs the Gardiners clay for some distance is not overlain by the Jacob sand. In places on the northwest coast, particularly at the mouth of Roaring Brook, the Jacob sand is absent and the Gardiners clay is present, but in practically all places where the Gardiners clay is exposed the Jacob sand overlies the greater part of the clay. The best exposures of the Jacob sand, both in development and in variation of structure, are seen in the Nashaquitsa cliffs. In places here it has been very much disturbed and compressed and it is locally overturned and removed from the Gardiners clay. Where the lateral compression has been great it has been thrown into small plications, and where it has been exposed to the action of the wind the thin beds, which contain more clay, stand out in relief, so that the deposit has a fluted appearance.

The general distribution of the Jacob sand on Marthas Vineyard may likewise be considered the same as that of the Gardiners clay. The Jacob sand flanks the northwest and southeast sides of the western area, surrounding a core of the older, more highly folded beds that form the backbone of this area. It is not seen in the town of Gay Head, and it probably lies below sea level in the northeastern part of the island. It has not been found below the outwash gravel of the great plain area, where there are no exposures deep enough to display it, but it may exist in this area.

Form of Surface

The form of the surface of the Jacob sand is due largely to the action of the Montauk ice. In places where the sand has been but slightly disturbed it passes upward gradually or fairly abruptly into the Herod gravel member of the Manhasset. In such places the surface of the Jacob has been undulated by the weight of the overlying ice. Where the Herod gravel was removed by the Montauk ice, or where it may never have been deposited, the upper surface of the Jacob sand is usually more irregular. In such places the action of the Montauk ice has been stronger and the Jacob sand has been pushed and dragged as well as eroded. At a few places till overlies the sand conformably, but generally the Jacob beds are greatly disturbed, as in the Nashaquitsa cliffs. As the Jacob sand overlies the Gardiners clay it was more exposed to the action of the ice and so has been more disturbed than the clay, but, owing to its content of silt, it acted in much the same way as the clay, being bent and folded rather than crumbled, as a coarser sand would have been.

Fossils and Age

The deposition of the Jacob sand immediately followed that of the Gardiners clay. The sand underlies the Manhasset formation without any sign of a break, and the deposition of these three formations was apparently fairly continuous. There is thus clear structural evidence that the Jacob sand is post-Gardiners and pre-Manhasset, or, in other words, that it is of about mid-Pleistocene age. It is a transitional formation between clay and gravel, but it is regarded by Fuller[1] as a deposit laid down during the Illinoian stage, in spite of the long time which intervened between its deposition and the actual invasion of the Montauk ice. Woodworth (pp. 37, 69 of this report) correlates it with the Yarmouth interglacial stage.

No fossils have been found in the Jacob sand on Marthas Vineyard, but some have been found in it on Long Island. Nearly all the forms found are still living in the waters of this region.

MANHASSET FORMATION

Name

The name Manhasset formation is applied collectively to a series of glacial deposits of post-Jacob and pre-Vineyard age. Although the formation is composed of three distinct members, formed by the ice that deposited the Montauk till, the deposits may be considered a unit. The top and bottom beds are of essentially the same character and would constitute a continuous bed were it not for the intervening bed of till. Regarding the origin of the name Fuller[1] writes: "The name is derived from Manhasset Neck [Long Island], along the shores of which, in the immense gravel pits on the Hempstead Harbor side, are to be seen exposures of these beds more than 100 feet in height. The name was first applied by J. B. Woodworth, who described and mapped in detail the deposits in a part of the west end of the island (Long Island)." The succession and nature of these beds on Marthas Vineyard, as well as their stratigraphic position, are in every way similar to those of the Manhasset formation on Long Island, and the same names are therefore here adopted for them. The term "Tisbury beds" was once used by Woodworth for a part of the Manhasset that was found along the northwest coast and that was approximately horizontal, but Woodworth's "Tisbury beds" included also the Jacob sand and Gardiners clay, and the name was abandoned by him.

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[1] *Op. cit.*, p. 113.

SUBDIVISIONS

The Manhasset formation is divided into three members — a lower bed, known as the Herod gravel, a middle bed, known as the Montauk till, and an upper bed, known as the Hempstead gravel. The upper and lower members are beds of similar glacial sand and gravel, and where the till bed is not present it is impossible to distinguish the Herod from the Hempstead. The Montauk till is easily recognized both by its position and its nature, the Wisconsin till being usually quite different, unless it lies directly on the Montauk till or has been formed of reworked Montauk material. These subdivisions of the Manhasset are the same as those on Long Island, and they are of essentially the same nature.

GENERAL DISTRIBUTION

The Manhasset formation is best seen along the shore of the western area and in Squibnocket, Stonewall Beach, and Nashaquitsa cliffs. It probably exists all along the shore of the western area and extends well up on the older core of the morainal highland. It also occurs in the northeastern area, but there it is not so well displayed and probably only its upper members are ever exposed. It doubtless underlies all the moraines of this area, although a large part of it is below sea level. Under the great plain the Manhasset no doubt underlies the outwash gravel, although it has not been clearly seen. Even if its upper member were exposed in this area it would probably be indistinguishable from the outwash gravel. From the great plain the Manhasset extends well up the southeast side of the core of the morainal highland in the western area.

HEROD GRAVEL MEMBER

Name.—"The name Herod gravel member is applied to the sand and gravel beds constituting the lower member of the Manhasset formation, or that part lying below the middle or Montauk till member. The name is taken from Herod Point, near Wading River, on the north shore of Long Island, where the gravel is well exposed."[1] The position and nature of these beds being exactly the same on Marthas Vineyard as on Long Island, the same name is here used for them.

Character. — On Marthas Vineyard the Herod gravel varies from a fine gravel to a sand. The change from gravel to sand in the vertical succession takes place abruptly, but the beds do not everywhere hold their character for any great distance horizontally. The gravel and sand are typical waterlaid glacial deposits derived from granitic rocks. The material in the gravel consists of quartz, fairly fresh feldspar, and other minerals. In addition to these finer constituents there are small pebbles, chiefly of igneous and metamorphic rock, and a small percentage of pebbles of sedimentary rock. Some of the pebbles were obviously derived from the earlier Pleistocene deposits and show considerable weathering, but the greater part of them are fresh and are typically waterworn. The sand in the Herod gravel consists largely of grains of quartz but includes small amounts of other minerals. Where the Herod gravel overlies a depression in the surface of the Jacob sand or the Gardiners clay it has been strongly stained, because the relative imperviousness of the underlying beds has allowed the water that seeped down through the overlying beds to collect and remain long enough to deposit some of the material that it contained in solution. Much of the material carried in solution by this water was probably derived from the Montauk till, some of whose constituents are very finely ground and evidently somewhat soluble. Even at present the water in wells in the region where the Montauk is found contains oxides of iron. The staining material is usually brown or red, but at some places, as at Norton Point, its color may be a bright orange-yellow, or it may be nearly black.

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[1] Fuller, *op. cit.*, p. 121.

Thickness.—The thickness of the Herod gravel differs greatly from place to place according to the extent of its erosion by the ice, as well as according to the probable original differences in it at the time of its deposition. Where no Montauk till overlies the Herod gravel it grades imperceptibly into the Hempstead gravel, which at such places cannot be distinguished from the Herod. The combined thickness of the two beds may therefore be mistaken for the thickness of the Herod alone. The maximum thickness of the Herod gravel, seen in Nashaquitsa cliffs, is about 100 feet. Elsewhere its thickness is much less.

Structure.—The Herod gravel is usually bedded, the beds consisting of layers of coarser and finer material. Many of the beds are horizontal, but where the whole member has been disturbed the beds conform to the distortion of the formation as a whole. The Herod gravel is probably made up of lenses of gravel and sand. The sand is in places 20 feet thick and contains no layer of gravel.

The Herod gravel as a whole, especially on the Vineyard Sound side of the western area, has been deformed by the Montauk ice, the deformation consisting largely of gentle folding and warping. The beds do not show the well-defined small foldings shown by beds of clay, their tendency under pressure being to crumble rather than to fold. For this reason folding is less common in the Herod gravel than in the underlying Gardiners clay and Jacob sand, and the sharp folds seen in those formations are not found in the Herod. The Herod was probably disturbed by the ice in two ways — first, by its push and drag, which would be especially effective where an escarpment in the gravel was exposed to the advancing ice; second, by the weight of the overriding ice, which caused unequal settling of both the Herod and the underlying clayey beds. In other words, much of the Herod gravel was exposed to both lateral and vertical pressure, to which it adapted itself as best it could in view of its loose and friable nature and its relations to the underlying formations. The Herod gravel that lies under the outwash gravel which covers the great plain area has probably been somewhat disturbed, for there is no reason to suppose that the Montauk ice sheet stopped before reaching this region. However, the ice probably did not encounter a rough surface, and it therefore probably overrode the Herod member without causing much deformation.

Source of materials.—The immediate source of most of the material of the Herod gravel is probably the older Pleistocene or earlier deposits of the same region and the region now occupied by Vineyard Sound. The original source must have been the mainland north of Marthas Vineyard. The granitic and gneissic pebbles, which are relatively fresh, may have come directly from the mainland.

Relation to other deposits.—At some places the Herod gravel grades down into the Jacob sand; at others it changes rather abruptly from coarse sand above to fine sand below. It therefore rests conformably on the Jacob sand and follows the undulations of its surface. Where the Jacob sand does not lie below it the Herod gravel may rest directly on the Gardiners clay or it may lie unconformably on earlier deposits, for the Herod gravel is a more extensive deposit than the Jacob or the Gardiners. The upper contact of the Herod gravel with the Montauk till is usually less disturbed and less irregular than would be expected. At some places there is an apparent conformity between the two beds, the unconformity seen at other places being due to erosion by the ice before it began to form deposits. In places the Montauk ice removed the Herod gravel entirely and the till rests on older beds. Where the Herod is in contact with the Montauk till the contact is sharp. At places where the Montauk ice did not deposit any till the upper surface of the Herod is in contact with the Hempstead gravel. At such places there must be an unconformity between the two, although it cannot be detected. ?

Conditions during deposition.— The conditions during the deposition of the Herod gravel were those due to an invading ice sheet. In addition there may have been a slight shallowing of the water, as the type of deposit formed suggests that the water was shallower than it was during the deposition of the Jacob sand; but the change in the type of deposit may perhaps be better explained by the change in conditions due to the approach of the ice. Deposition was greatly accelerated by the increase in the volume of water pouring from the melting ice and by the increase in the amount of material fed to the water by the ice. The climate was probably colder and precipitation was probably greater in Herod than in Gardiners and Jacob time. The currents were stronger, and other agencies were more active. Near the end of Herod deposition the water in this region had grown much shallower, largely because of the great quantity of gravel laid down.

Distribution.— The Herod gravel is the most widely distributed member of the Manhasset formation, the Montauk and Hempstead members being of smaller areal extent. The Herod probably covers a larger area than any other Pleistocene deposit on Marthas Vineyard. The smaller areal extent of the two later Manhasset members is not due to their smaller areal deposition but to their greater erosion during the Vineyard stage, which preceded the Wisconsin stage. The Herod gravel flanks both sides of the western area and doubtless underlies both the northeastern area and the great plain. It is well exposed in the Stonewall Beach (fig. 15), Nashaquitsa, Cedar Tree Neck (figs. 14 and 16), and Gay Head cliffs. Along the northwest shore it is seen in nearly all the cliffs, especially north of Prospect Hill and at Norton Point. As the Herod gravel is much like the Hempstead and the Wisconsin gravel, it cannot easily be distinguished from these in the interior of the island, for exposures are scarce and more than one formation must be exposed in order to permit identification of any one. Where the Montauk till and an underlying gravel are exposed the gravel is usually the Herod. Some such exposures are seen along the State road in Gay Head and Nashaquitsa, but very few are seen on the roads in the rest of the western area.

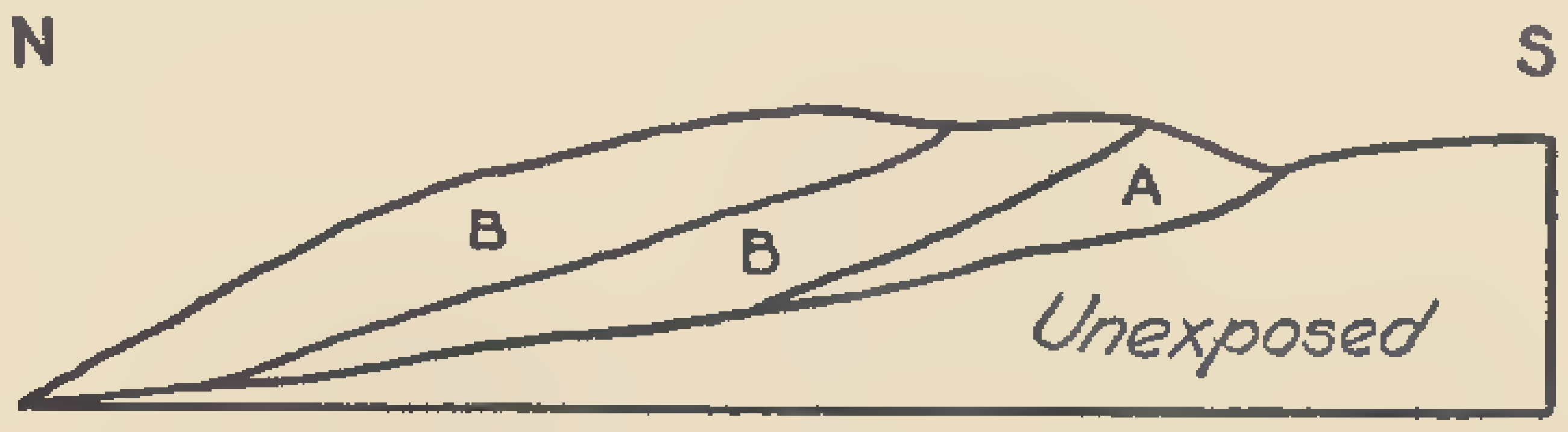

FIG. 14.— Section one mile south of Cedar Tree Neck. Manhasset formation in morainal topography. A, Herod gravel member; B, Montauk till member.

Age.—The position of the Herod gravel, which lies above the Jacob sand and below the Montauk till, shows that it is one of a series of beds that are connected with the advance of the Montauk ice. These beds, including the later Hempstead gravel, all form a larger unit. On Long Island these beds, which compose the Manhasset formation, are regarded as equivalent to the Illinoian by Fuller,[1] whose view seems to be supported by the evidence on Marthas Vineyard.

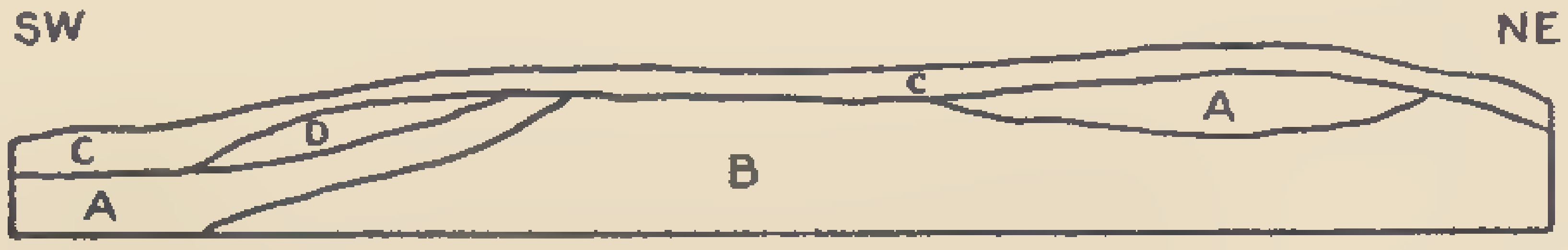

Fig. 15.— Section at Stonewall Beach cliffs. A, Montauk till; B, Herod gravel; C, Wisconsin till; D, clayey phase of Montauk till.

MONTAUK TILL MEMBER

Name.—The Montauk till was named from Montauk Point, Long Island, where it is well exposed. The name is applied to the middle of the three subdivisions of the Manhasset formation.

Character.—The Montauk till is the most conspicuous of the Pleistocene deposits, and it differs greatly from all the others. It is made up of a mixture of clay, sand, pebbles, and boulders, which form a very compact tough bed of unmistakable till. (See Plates **24** and **25**, fig. 1). Its composition on the whole is fairly uniform, but in places it is very clayey, particularly near the Gardiners clay, where it is composed of material reworked from that bed. In some of its exposures the Montauk is banded, in others it is massive. Its toughness, which is one of its most notable features, is undoubtedly due to compression and partial cementation, which have produced a bed of hard pan that cannot be penetrated with a shovel. A secondary feature is its mode of erosion. Where it has been eroded by rain it has been cut into steep-sided gullies separated by pinnacles. (See Plate **25**, fig. 1). Some areas of eroded Montauk resemble badlands.

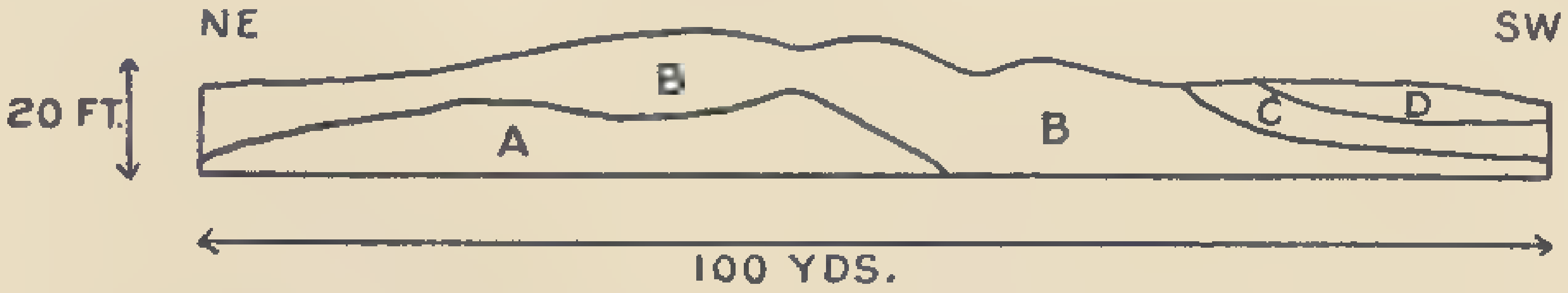

Fig. 16.— Section exposed southwest of Cedar Tree Neck. A, Herod gravel; B, Montauk till; C, gravelly phase of Montauk till; D, either Wisconsin or Hempstead sand.

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[1] Fuller, M. L., *op. cit.*, p. 132.

Fresh exposures of the till are bluish-gray, but this color is seen only in the lower part of a bed. The upper part is usually brownish, or even chocolate-colored, a shade due to the oxidation of some of the iron in the till. Where the till is made of largely reworked Gardiners clay it has the dark gray or nearly black color of that bed. Most of the boulders in it are granite and gneiss, but it contains many other kinds of rock. Some of the boulders and pebbles are angular and show strong glacial striation. The largest boulders are 6 feet in diameter, but many exposures show scarcely a boulder over a foot long.

Thickness.—The maximum thickness of the Montauk till on Marthas Vineyard is 40 feet.

Source of material.—The material of the Montauk till is obviously glacial. The heterogeneous mixture of boulders, gravel, and clay and the shape of the larger constituents and their characteristic markings show conclusively a glacial origin. The coarser constituents of this till must have come from the mainland on the north, for such rocks are not found in place nearer than the north side of Buzzards Bay. The finer constituents were probably derived from the older Pleistocene beds, all of which show considerable erosion by the Montauk ice. The gravel must have been in large part derived from the Herod gravel, and perhaps in less amount from earlier gravel. The clayey elements and the rock flour produced by the Montauk ice were probably derived from the Gardiners clay and the Jacob sand; in fact, parts of the Montauk till closely resemble the Gardiners clay and are undoubtedly made up of reworked clay of that member. It is impossible, however, to determine the sources of all the material. Some of it may have been brought from the area now occupied by Vineyard Sound and Nantucket Sound.

Relation to other deposits.—At some places the Montauk till rests conformably upon the Herod gravel; at others it rests unconformably upon the Jacob sand or the Gardiners clay. The contact is usually marked by disturbances such as would be made by an ice sheet overriding unconsolidated beds. These disturbances consist of the removal of some part of the lower beds and the warping, folding, and even faulting of the part of the bed that lies directly in contact with the till.

The Hempstead gravel rests conformably on the Montauk till. This gravel, however, is not nearly so extensive as the Herod, and at some places the Montauk is overlain directly by the Wisconsin. At many places where the contact between the two cannot be seen it is impossible to distinguish the Hempstead from the Wisconsin. If the contact is conformable the gravel must be the

Hempstead; if it is unconformable it is the Wisconsin. A long period of erosion followed the deposition of the Hempstead, and where the Wisconsin till rests upon the Montauk it may be difficult to tell where the Montauk ends and the Wisconsin begins.

Structure.— The Montauk till is gently warped and folded, but many of its variations from horizontality are no doubt due to irregularities in the surface on which it was deposited. It was not laid down horizontally, as were the water-laid deposits. Such deformation as it has undergone must be due to the action of the Wisconsin ice sheet, which was relatively weak on Marthas Vineyard, owing to the interlobate axis there, and could not have caused the disturbances found in the beds below the Montauk in other regions. The surface in the Vineyard interval was overridden by the Wisconsin ice but was not greatly disturbed.

Conditions during deposition.— The conditions that prevailed during the Montauk stage of the Manhasset were those that are associated with a vigorous continental ice sheet. The area that now forms Marthas Vineyard was covered by a thick glacier, which extended at least to the southern limit of the island and probably beyond. The extent of the deposits of Montauk time indicates a much more vigorous or longer action of the ice than that in Wisconsin time. The great thickness of the ice is indicated by the distortion of the older beds, which may be attributed to the downward pressure of overlying ice without horizontal pressure. The region must have remained buried under the ice for a long time, for the till laid down is thick and there is nowhere any evidence that it accumulated rapidly. Toward the end of this stage there naturally must have been a stage when the ice was stagnant and melting—a stage at the beginning of Hempstead time. After this great ice sheet had disappeared the region must have presented a picture that surpassed in desolation and barrenness anything now in existence.

Distribution.— The Montauk till probably underlies the greater part of Marthas Vineyard, but it is exposed only in its western part, except in two areas. These areas are in the northeastern part of the island, near Edgartown, and on Chappaquiddick Island. The first exposure indicated is in a gravel pit at the side of the State road about a mile from Edgartown, where a lower tough bed of till lies beneath bedded gravel, which is in turn overlain by sandy Wisconsin till. The second exposure is on the east side of Sampson Hill, on Chappaquiddick Island, where a small gravel pit exposes the tough till below the Wisconsin. In addition to these exposures there are a few places in the northeastern area where the Montauk may be exposed. In Edgartown village a man who has dug many wells says that a bed of tough hard pan containing pebbles lies beneath several feet of loose gravel. South of the Edgartown-Vineyard Haven road, a little more than a mile west of Edgartown, there is an area of clayey till, used for road material, which is distinctly different from any Wisconsin material. Unfortunately, its relations to the other deposits cannot be determined. Its striking characteristic is its reddish color. In its nature it is more like Montauk than Wisconsin. This exposure is in what the natives call "the red ground." This red ground is elsewhere poorly exposed, but traces of it found in the northeastern area extend somewhat north of west from this locality along the northern edge of the great plain, especially near the superintendent's house on the State game reservation. The same material is found just north of the State road about a quarter of a mile west of the head of Chappaquonsett Pond, in the western area.

. The Montauk till is exposed at many places in the western area. The best exposures are in the cliffs, and those at Squibnocket are the most noteworthy. (See fig. 17). Here the cliff is made up largely of this member and shows zones of different color. The upper part here is brownish, a color quite different from that of the chocolate-colored till below it. Below the chocolate-colored till there is a grayish till. Some of the coloration here is undoubtedly due to weathering, but some is original, for near its base the till is at some places composed of Cretaceous clay and at others of the Gardiners clay. At the west end of the Squibnocket cliff the Wisconsin overlies the Montauk. Elsewhere in the section it is hard to make out any Wisconsin covering. It may exist here, but it is probably similar to the Montauk.

In about two-thirds of the section at Squibnocket cliff the Montauk till overlies the Herod gravel, below which, for a short distance, the Jacob sand and Gardiners clay are seen. The typical erosion forms of the Montauk are seen here better than anywhere else, and on this account this shore closely resembles the south shore of Block Island. The formation is eroded into sharp gullies, intervening pinnacles, and minaret-like forms, such as are seen in badland topography. (See Plate **25**, fig. 1.) Here and there large boulders are imbedded in the till, and the whole shore here is a bouldery beach, which owes its character to these erratics from the Montauk.

Other exposures of the Montauk till are seen in the Stonewall Beach cliff, at the west end of Nashaquitsa cliffs, and on Gay Head. The Montauk is probably rather widely distributed through the town of Gay Head and lies very near the surface. It is seen in several exposures along the State road. (See Plate **24**.) Along the north side of Gay Head the till is covered by more gravel than elsewhere.

Along the northwest shore of the main island there are many exposures of Montauk till. In the Norton Point cliffs it is not well exposed, although it is seen at some places. It is exposed immediately west of Paul Point, and at Cedar Tree Neck there is a small cliff composed entirely of the Montauk till which, however, presents a nearly vertical face, without the typical erosion forms. This peculiarity is due to the fact that no streams flow over the cliff, the rainfall from the cliff flowing down the slope to the small pond back of the shore. The cliff is therefore eroded only by the waves. From Cedar Tree Neck to Cape Higgon practically all the bluffs expose Montauk beds. At Cape Higgon itself very little is seen, but in the cliffs northeast of Roaring Brook the till is seen again above the Herod gravel and Gardiners clay. From Roaring Brook to Menemsha the Montauk till appears in places, especially west of Prospect Hill. For the details of the occurrence of the Montauk till along the shore, reference should be made to the diagrams showing sections of the cliffs.

Age.— The stratigraphic position of the Manhasset formation, of which the Montauk till is the middle member, can clearly be established as post-Jacob and pre-Vineyard. It overlies the Jacob sand at many places, yet it was subject to extensive erosion during the Vineyard interval. There is no evidence of an ice advance between the Montauk till and the Wisconsin moraine. The erosion during the Montauk interval was deep and must have been rather long as compared with the post-glacial erosion of the beds of clay and sand of the island by streams and rainfall. The Manhasset and its included bed of Montauk till are clearly the products of a glacial stage prior to the Wisconsin stage and separated from it by a long interglacial stage of fluvial conditions. The Manhasset may be the eastern representative of the Illinoian drift. The Manhasset and its intercalated bed of Montauk till constitute the thickest glacial deposit on Marthas Vineyard, agreeing in thickness with the Illinoian drift of the Mississippi valley, which is somewhat greater than that of the Wisconsin.

Hempstead Gravel Member

Name.—"After the Montauk invasion and its attendant [ice] erosion, deposition, and folding, the ice retreated from Long Island and a series of gravels were laid down, doubtless derived from the ice, which appears to have lingered in the vicinity. For these gravels, which represent the uppermost of the three

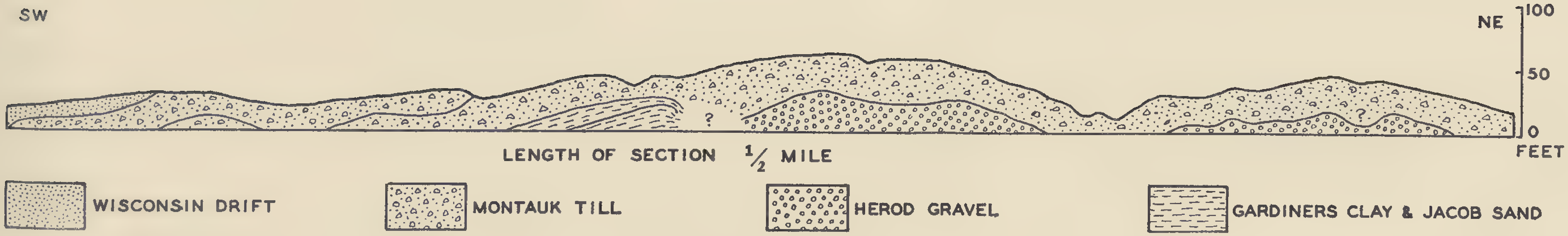

Fig. 17.— Section in cliffs at Squibnocket.

subdivisions of the Manhasset formation, the name Hempstead gravel member is here introduced, from Hempstead Harbor, along the west side of which the gravel is finely exposed in the upper parts of many large gravel pits."[1] The conditions of deposition and the stratigraphic position of the gravel on Marthas Vineyard seem to have been the same as on Long Island, and the same name is therefore retained for this deposit.

Character.— Of the upper divisions of the Pleistocene the Hempstead is by far the most indefinite. At many places it cannot be distinguished from the Herod or from the Wisconsin. Over the greater part of the island it appears to be lacking. A few sections, however, seem to prove its presence.

The Hempstead gravel on Marthas Vineyard is lithologically exactly like the Herod. What has been said here in regard to the character of the Herod applies equally well to the Hempstead. This member, however, is not so widely distributed, because much of it was removed during the following period of erosion. Were it not for its position above the Montauk till this member could not be distinguished from the Herod, and where the Montauk or other key beds are absent or not exposed it is impossible to distinguish them.

Thickness.— The thickness of the Hempstead gravel cannot be given positively on account of the erosion it has undergone and the scarcity of the exposures. The section at Cape Higgon, if correctly interpreted, shows the greatest thickness exposed anywhere. Here there are about 40 feet of gravel whose base is exposed only where a large amount has obviously been removed from the surface. In other words, this figure may be no more than a minimum one.

Source of materials.—The source of the material of the Hempstead is essentially the same as that of the Herod. Both were abraded from the same region and by the same ice sheet. The glacial front in Hempstead time, however, was retreating, whereas in Herod time it was advancing.

Relation to other deposits.—The Hempstead gravel overlies the Montauk conformably, and the contact is fairly sharp. The Wisconsin drift lies unconformably upon the Hempstead. This unconformity is due to the normal erosion of Vineyard time, which preceded the advent of the Wisconsin ice and lasted long enough to remove much of the Hempstead gravel and to develop a mature system of drainage.

Structure.— The Hempstead gravel has been much less disturbed than any of the preceding deposits. Indeed, owing to its thinness or its short duration, the Wisconsin ice sheet was so weak that the beds which it overrode were practically not deformed by it. The only places where any distortion could possibly be made out would be those where the ice front encountered a cliff or other abrupt topographic feature. Being a waterlaid deposit, the gravel shows bedding wherever it is exposed. It contains no beds of till that might have been formed by re-advances of the ice, such as are found in parts of Long Island. Some thin layers of clay, however, are found in beds of gravel that probably belong to the Hempstead.

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[1] Fuller, M. L., *op. cit.*, p. 150.

Conditions during deposition.— The Hempstead gravel was laid down when the ice was retreating, a fact that suggests a somewhat milder climate than that which prevailed during the Montauk stage, although the retreat may have been due solely to a slackening in the speed of the advancing ice. At any rate, the time was one of melting; water from the ice was washing materials out of it and depositing them. Vegetation was probably very scarce, so that the deposits were subject to rapid erosion.

Distribution and outcrops.— The Hempstead gravel is found only along the northwest and northeast shores of Martha's Vineyard and in the inland areas that border these shores. Beds of gravel of this age may lie below the outwash gravel in the great plain area, but they have not been recognized; in fact, it would be impossible to distinguish them from the overlying outwash unless an unconformity could be recognized between the two.

Northeast of Menemsha Creek, in the cliffs along the shore, some beds of sandy gravel that are supposed to be Hempstead are exposed above the Montauk till. Farther northeast no beds of gravel that can be placed at this horizon are seen until the section northeast of Roaring Brook is reached. Near the northeast end of this section there is a small patch of sandy gravel, which overlies the Montauk till conformably and is in turn overlain by the Wisconsin till. The largest exposure of probable Hempstead gravel is at Cape Higgon. Here some beds of sandy gravel, exposed to a thickness of 40 feet, seem to overlie the Montauk. This gravel is exposed for about 500 feet along the cliff. Another exposure occurs a little more than a third of the way from this point to Cedar Tree Neck, where gravelly sand and laminated fine sand and clay overlie the Montauk till. In the cliff just south of Cedar Tree Neck there is an obscure section showing bedded sand, probably of Hempstead age, overlying the Montauk till. The sandy gravel northeast of Cedar Tree Neck is also probably Hempstead. In the Norton Point section some of the uppermost beds of gravel are perhaps Hempstead, although the Montauk till is but poorly exposed.

West Chop and East Chop cliffs are probably composed largely of beds of Hempstead gravel and overlying Wisconsin till. These beds have been only slightly disturbed. As the Montauk is nowhere exposed, and as it appears at successively lower levels east of Norton Point, it probably lies below these beds of gravel. It is possible, however, that these beds are Wisconsin deposits that accumulated in the interlobate area as the ice front was retreating. The cliffs on both sides of Lagoon Pond are also probably composed of beds of Hempstead gravel, although the beds are overlain by considerable sandy and gravelly till. This till is of Wisconsin age and seemed to be composed largely of reworked Manhasset gravel, but the contact between the two is obscure.

The cliff on the north shore of Chappaquiddick, about 2 miles east of Edgartown, shows thick beds of gravel that are here also regarded as Hempstead.

Age.— The Hempstead gravel represents the closing stages of Manhasset deposition, when the Montauk ice front was retreating. Its deposition followed closely that of the Montauk till, but antedated by a long time the deposition of the Wisconsin. According to the correlation indicated previously in this report, the Manhasset is Illinoian; and as the Hempstead is the uppermost member of the Manhasset it is therefore late Illinoian.

VINEYARD INTERGLACIAL STAGE

At the end of Manhasset deposition, before the advance of the Wisconsin ice sheet, there was a long period of normal subaerial erosion, during which a mature system of drainage was developed on Marthas Vineyard. The topography of that time is still preserved in the western area, and, though less completely, in the northeastern area. During this period of erosion the land evidently stood higher than it stands now, for its eroded surface now lies below sea level. This period was obviously long, much longer than the time that has elapsed since the Wisconsin ice invasion, for the erosion then was much greater than that which has taken place since Wisconsin time.

Shaler[1] presented the evidence of this period of erosion in 1888 and again in 1890, and Woodworth[2] called the period the Vineyard interval in 1896. In regard to its age Woodworth[3] writes:

> This erosion epoch, which may be known as the Vineyard interval, corresponds to the long inter-glacial epoch which has been so often pointed out by various evidences outside of

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[1] Shaler, N. S., Report on the geology of Marthas Vineyard, Seventh Ann. Rept., U. S. Geol. Survey, p. 345, 1888; Tertiary and Cretaceous deposits of eastern Massachusetts, Bull. Geol. Soc. Am., **1**, p. 448, 1890.

[2] Woodworth, J. B., in The glacial brick clays of Rhode Island and southeastern Massachusetts, by N. S. Shaler, J. B. Woodworth, and C. F. Marbut, Seventeenth Ann. Rept., U. S. Geol. Survey, pt. 1, pp. 979-980, 1896.

[3] Woodworth, J. B., *op. cit.*, pp. 208-209.

New England. It constitutes the last and the most marked unconformity by erosion on the island of Marthas Vineyard.

The Vineyard interval was mainly a period of erosion, but a few small beds of peat were then formed. These beds seem to lie below the Wisconsin and recent deposits and above the Manhasset. Such beds of peat, which contain stumps of trees, have been seen at places on the southwest shore of Gay Head, on the northwest shore, and on Squibnocket. All these beds except those on Squibnocket lie nearly at sea level. Similar beds at this horizon on Long Island are mentioned by Fuller.[1]

WISCONSIN DRIFT

Subdivisions

The Wisconsin drift is the last glacial deposit laid down and is therefore the highest division of the Pleistocene series. Its type area is in Wisconsin, from which it was named. Chamberlin,[2] Wright,[3] and others have traced it from this region to Wisconsin and have established its identity in the intervening country. As it is the uppermost glacial formation it is not concealed by overlying deposits and can therefore be studied much better than any of the others. Its diversity here is greater than that of any of the earlier Pleistocene beds, because during one stage of the Wisconsin glaciation this region was occupied by the ice front. It includes three distinct types of deposits, (1) the sheet of till or ground moraine; (2) the frontal moraine, here part of the terminal moraine, the outermost frontal moraine of this ice sheet; (3) the outwash from the ice along the frontal moraine.

The Till Sheet

Character.—The till or ground moraine is a deposit laid down beneath the ice. It is composed largely of unassorted gravel, which was of local origin and was dragged along under the ice or liberated from the bottom of the ice by melting. The till on Marthas Vineyard contains very little clay; it is composed mainly of granitic gravel, which is at many places difficult to distinguish from gravel of different origin, whose bedding has been obliterated by overriding ice or for some other reason is not apparent. When it is closely examined, however, an occasional pebble that shows faint glacial striae may be found. To some extent the Wisconsin till varies in its nature according to the deposits which it has overriden, but as these consisted predominantly of gravel, the till is also mostly gravel. Where it rests on the Montauk till it partakes to some extent of the nature of that bed.

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[1] *Op. cit.*, p. 157.

[2] Chamberlin, T. C., Preliminary report on the terminal moraine of the second glacial epoch, Third Ann. Rept., U. S. Geol. Survey, pp. 291-402, 1882.

[3] Wright, 1883, G. F., The glacial boundary in western Pennsylvania, Ohio, Kentucky, Indiana, and Illinois, Bull. U. S. Geol. Survey, **58**, pp. 39-110, 1890.

The Wisconsin till is at some places at least 10 feet thick, and in certain small areas it may be thicker, but it is almost absent at many places where one would expect it to be thickest. Such places are especially numerous in the western area. The till contains no clay and has a loose gravelly structure, differing strikingly from the Montauk till, which is always tough and compact and shows no tendency to slide where it is exposed in cliffs or banks. Exposures of the Wisconsin till that have been opened for only a short time are usually covered with talus. The till is usually not very coarse, the diameter of most of the pebbles being less than 2 inches and the matrix usually being sandy. It contains some boulders, but they form only a small part of it. The greater part of the boulders on the island belong not to the till but to the frontal moraine.

Source of material.—Most of the material of the Wisconsin till was derived from the Pleistocene beds over which it moved, and as these beds consist mostly of unconsolidated gravel and sand the till is loose and gravelly. Its boulders, except those that were picked up from the Montauk deposits, must have come from a greater distance. All its material, both coarse and fine, before it was transported and deposited in earlier Pleistocene time, must originally have been brought from the mainland on the north.

Relation of the Wisconsin to earlier deposits.—The Wisconsin till lies unconformably upon the Manhasset formation and other earlier deposits. The surface formed during the Vineyard interval is thus covered by this thin mantle, irrespective of hills or valleys, except at some places in the higher parts of the western area, where the till is either lacking or is so thin as to be indistinguishable. The sheet of till shows no disturbances such as are seen in all the earlier deposits, having apparently been laid down very gently. The contact between the till and the beds on which it lies is at few places sharp, or at least it cannot be clearly seen, because the underlying bed and the till are very much alike and the uppermost layers of the lower bed have been somewhat dragged, and so, in a sense, incorporated in the till. Where the till overlies a bed of different nature, such as the Montauk or the Gardiners, the contact may be sharp.

Distribution.—The Wisconsin till is found only in the western and northeastern areas and in a zone along the northeast edge of the great plain, where, near the end of its stay, the ice extended temporarily over the outwash. In the northeastern area the till is very sandy, but it is fairly well distributed among kame deposits. It is seen in typical form in exposures along the banks of Lagoon Pond and in East Chop cliffs, although it is rather thicker at these places than elsewhere. In the western area the till is somewhat coarser and is rather widely distributed. It can be seen in almost any of the cliffs along the shore of Vineyard Sound. In the region south of the middle road it is very thin, and was at one time even thought to be absent. The history of late Wisconsin time in this region seems to have been similar to that in the northeastern area. Near the end of the Wisconsin stage the ice advanced temporarily, as is shown by the ice-contact slope north of West Tisbury post office and by several exposures of till along the border of the great plain, as well as by occasional surface boulders. During this advance a thin coating of till was laid down, which in some places, especially on the higher ground, may now be almost removed.

NANTUCKET MORAINE

Origin and character.—The deposits that form the Nantucket moraine were laid down along the ice front. They were in part deposited directly by the ice, but most of them show bedding and were therefore laid down in water. The gravel in them is typical coarse granitic glacial gravel, which seldom occurs in horizontal beds because it was "dumped" in masses in front of the ice. The form of the surface of these deposits is peculiar and is one means of identifying them. The numerous large boulders that cover the surface of these morainal deposits are perhaps their most conspicuous feature. These boulders are obviously ice borne and must have come from a great distance, or at least from parts of the mainland where bed rock of the same kind is found in place. Some of the boulders have probably traveled 60 miles from their parent ledges.

The most conspicuous part of the Nantucket moraine lies between Chappaquonsett and Nashaquitsa and was formed by the Buzzards Bay lobe of the Wisconsin ice sheet. The materials in this part of the moraine are coarser and the boulders are more numerous and larger than those in the limb of the moraine formed by the Cape Cod Bay lobe, which extends from the head of the interlobate angle southeastward along the shore of Nantucket Sound to Edgartown and across Chappaquiddick Island. The material in this part of the moraine usually consists of gravel and sand and till. The source of the material of both parts of the moraine was the mainlaid on the north, but as the two lobes of ice came from different parts of the mainland they brought somewhat different materials.

The western limb of the moraine rests on the eroded surface of older Pleistocene deposits and on Tertiary and Cretaceous beds. These older deposits in this region form an elevated plateau on which the moraine is superposed. The northeastern limb of the moraine probably lies on the Manhasset formation, but this formation is exposed at but few places. This part of the moraine does not rest on an elevated tract, as does the other. The morainal deposits vary in thickness because they consist of ridges. Their average thickness is probably not more than 5 or 10 feet.

Distribution.—The morainal deposits in the town of Gay Head consist of bedded gravel and sand, which form ridges that overlie the Manhasset and older beds. The moraine here is not so conspicuous as it is in Chilmark, but on Nashaquitsa there are prominent typical morainal ridges and knobs. Many of these ridges are distinctly kamelike; and the bedding also suggests kames. The deposits in Stonewall Beach cliffs rest on the Manhasset formation, and those along the shore of Menemsha Pond rest on the Gardiners clay.

The most extensive morainal area and the largest frontal moraine is in Chilmark. The deposits begin on the east side of Menemsha Pond and rise rapidly to a height of more than 300 feet in Prospect and Peaked Hills, from which they extend northeastward, with interruptions, as far as the region about Norton Point. Their higher parts stand well above 200 feet. Prospect Hill is the most striking morainal ridge on the island, standing up as an isolated hill. A ridge that runs parallel to the north road, southeast of Prospect Hill, is also typical. The best example of general morainal topography may be seen in the region east of Peaked Hill, and here also Cretaceous deposits are exposed at the base of the ridges in the high area. In Chilmark the moraine is separated longitudinally into two parts by the north road valley. (See Plate 16, fig. 1.) The moraine south of this valley is continuous from Peaked Hill almost to North Tisbury and is a remarkable morainal highland. The moraine north of this valley extends from Menemsha Creek through the town of Chilmark and beyond, nearly to Chappaquonsett Pond. The topography of this moraine is more accentuated than that of the other and is, perhaps, best shown near the Chilmark-West Tisbury town line. (See Plate 15, fig. 1.) The deposits here form two sharp ridges that run parallel to the shore and that contain many boulder belts. (See Plate 17, fig. 2.) This moraine is interrupted by several pronounced breaks. One of these breaks, if Nashaquitsa or Gay Head is considered a part of this moraine, is made by Menemsha Pond; another is made by Roaring Brook; and a third by Howlands or Paint Mill Brook. The fact that these two streams were able to maintain their courses in spite of the deposition of the moraine is noteworthy.

In West Tisbury the moraine reaches its best development in the Indian Hill region. Beyond this it is interrupted by James Pond and the valley southeast of it.

In the region about Chappaquonsett Pond the direction of the morainal belt was changed by the interlobate re-entrant in the ice front, and there the character of the topography and the nature of the deposits are somewhat modified. Between Lagoon Pond and the State road on the west there are sandy morainal deposits but no sharp ridges. Similar deposits are seen on the east side of Lagoon Pond and farther southeast, where the morainal area grows narrower, especially near Sengekontacket Pond. (See Plate **17**, fig. 1.) Exposures are scarce in this whole region, and the till cannot easily be separated from the bedded deposits. The difference in the topography and the morainal deposits here and those in the western area is probably due to a re-advance of the ice after the moraine had been formed. The morainal deposits of the Cape Cod Bay lobe have been described as "kame-moraines." The ice that moved over the moraine modified the form of the ridges and converted much of the surface material to a sandy till, which overlies the morainal deposits that have the bedding of kames.

The moraine continues beyond Sengekontacket Pond but is interrupted at Edgartown by the narrow strait that connects Edgartown Harbor and Katama Bay. On Chappaquiddick the moraine grows much broader and finally it becomes lower and disappears under the sea at the east side of the island.

Outwash Deposits

The outwash deposits of the Wisconsin stage lie in the great plain south of the Nantucket moraine. (See Plate **15**, fig. 2). The material of this outwash varies from coarse gravel containing rather large pebbles to sand, and it is coarsest along its northern boundary. In the southern area the upper layers are coarser than the lower ones. No boulders are found in the outwash gravel, which contains pebbles of many kinds of rock. Exposures of the outwash are very scarce, for its deposits are flat and the area it occupies has not been inhabited by man. The beds of outwash seen in the banks of the ponds in the southern part of the plain appear to lie nearly horizontal, although they probably dip gently to the south.

The material of the outwash was brought to this region by the ice, from which it was carried out and deposited by glacial streams. Most of these streams issued from the base of the ice and therefore contained a larger proportion of local material than the morainal gravel. Much of the outwash gravel was probably derived from the earlier Pleistocene deposits of this region from those of the region just to the north. Most of the after outwash probably came from the Cape Cod Bay lobe, for all branches of Tisbury Great Pond and the ponds east of it head toward this lobe and not toward the Buzzards Bay lobe, although that was much nearer. The main streams, at least near the end of Wisconsin time, came from the northeast, and as they were the means of transportation the material doubtless came from the same direction.

The Manhasset formation probably underlies most of the outwash, and no doubt early Pleistocene deposits as well as the Cretaceous beds underlie in places both the Manhasset and the outwash. The surface of the Manhasset must have been considerably eroded during the Vineyard interval, and probably the great volume of water issuing from the Wisconsin ice further eroded and re-deposited parts of that series. Thus the outwash deposits must rest unconformably on the older beds, although the form of the general surface of those beds may not have been much different from that of the surface of the present outwash.

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1893. **Bryson, John.** The glacial geology of Marthas Vineyard compared with that of Long Island: Am Geologist, **11**, pp. 210 212.

Points out the striking similarity between the two areas. Differs with Shaler in regard to the origin of the outwash plain and its channels —believes these were formed by waters flowing from the glacier. Thinks that the submerged tree stumps do not necessarily indicate submergence.

1893. **Hollick, C. Arthur.** Observations on the geology and botany of Marthas Vineyard: Trans. New York Acad. Sci., **13**, pp. 8–22.

Reviews the previous descriptions of the geology of the island and adds results of his own observations. Compares the geology of Staten Island and Long Island with that of Marthas Vineyard. Ascribes the structure of the beds on all three islands to ice shove.

1894. **Dall, W. H.** Notes on the Miocene and Pliocene of Gay Head, Marthas Vineyard, Mass., and on the "land phosphate" of the Ashley River district, S. C.: Am. Jour. Sci., 3d ser., **48**, pp. 296–301.

Gives a list of Miocene and Pliocene fossils from Gay Head and Chilmark, which he has identified. Describes two species.

1894. **Hollick, C. Arthur.** Dislocations in certain portions of the Atlantic Coastal Plain strata and their probable causes: Trans. New York Acad. Sci., **14**, pp. 8–20. Abstract, with discussion by N. S. Shaler, in Bull. Geol. Soc. America, **6**, pp. 5–7; Am. Geologist, **14**, pp. 197–198.

Upholds Merrill's view that the dislocations of the Coastal Plain strata are due to the action of ice. Gives several arguments in support of this view.

1894. **Shaler, N. S.** Pleistocene distortions of the Atlantic seacoast: Bull. Geol. Soc. America, **5**, pp. 199–202. Abstract in Am. Geologist, **13**, 143–144; Am. Jour. Sci., 3d ser., **47**, p. 138.

Contends that the folding in the older beds on Marthas Vineyard can not be attributed to the action of ice, because there was a well-developed pre-glacial topography, now identified as pre-Wisconsin. Does not admit the possibility of an earlier ice advance.

1894. **Woodworth, J. B.** Postglacial æolian action in southern New England: Am. Jour. Sci., 3d ser., **47**, pp. 63–71.

Describes several places on the island where postglacial æolian action occurs.

1895. **Hollick, C. Arthur.** Marthas Vineyard Cretaceous plants [abstract]: Bull. Geol. Soc. America, **7**, pp. 12–14; Am. Geologist, **16**, p. 239; Science, new ser., **2**, p. 281.

Describes about a hundred species of fossil plants, which he assigns to middle Cretaceous time. Regards them as closely related to those collected from deposits on Long Island and Staten Island equivalent to the "Amboy clay series."

1895. **Ward, L. F.** The Potomac formation: U. S. Geol. Survey Fifteenth Ann. Rept., pp. 307–397.

Regards the Cretaceous deposits on Marthas Vineyard as the latest phase of the Potomac.

1896. **Marsh, O. C.** The Jurassic formation on the Atlantic Coast: Am. Jour. Sci., 4th ser., **2**, pp. 443–447; Science, new ser., **4**, pp. 805–816.

Believes that the clays exposed on Marthas Vineyard are Jurassic, because of their resemblance to the clays of Wyoming and Utah.

1896. **Shaler, N. S., Woodworth, J. B., and Marbut, C. F.** The glacial brick clays of Rhode Island and southeastern Massachusetts: U. S. Geol. Survey Seventeenth Ann. Rept., pt. 1, pp. 951–1004.

Establishes the age of the older beds. Describes the nature and succession of the Pleistocene deposits. Shows that the glacial epoch included three great periods of ice action, which were separated from one another by long intervals.

1896. **Ward, L. F.** Age of the island series: Science, new ser., **4**, pp. 757–760.

States that the fossil flora of the clay beds give indisputable evidence of their age.

1897. **Woodworth, J. B.** Unconformities of Marthas Vineyard and of Block Island: Bull. Geol. Soc. America, **8**, pp. 197–212. Abstract in Jour. Geology, **5**, pp. 96–97; Science, new ser., **5**, pp. 86–87.

Describes in detail the structure and succession of the beds at Gay Head. Lists seven unconformities. Gives a section of the Gay Head cliffs. Discusses the cause of the folding and overthrusting and states that absolute proof of the theory of ice thrust is lacking. States that if this theory is to be accepted the supposed results must be attributed to two ice advances, which were separated by a long interval. Both of these advances must have preceded by a long time the last advances.

1898. **Dall, W. H.** A table of the North American Tertiary horizons correlated with one another and with those of western Europe, with annotations: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 2, pp. 327–348.

Includes the "Gay Head sands" under the Pleistocene and the "Gay Head gravels" under the Miocene. The tables show the relative position of these beds and those of the same epochs in other parts of North America and Western Europe.

1898. **Shaler, N. S.** Geology of the Cape Cod district: U. S. Geol. Survey Eighteenth Ann. Rept., pt. 2, pp. 497–593.

Contains one chapter presenting a brief summary of the geology of Marthas Vineyard. Adheres, in the main, to his previous views.

1898. **Woodworth, J. B.** Some glacial-wash plains of southern New England: Bull. Essex Inst., **29**, pp. 71–119, Salem, Mass.

Includes description of the Marthas Vineyard plain, which appears to have risen in the angular space between the two lobes of the ice front.

1899. **Upham, Warren.** Glacial history of the New England islands, Cape Cod, and Long Island: Am. Geologist, **24**, pp. 79–92. See U. S. Geol. Survey Mon. 33, p. 113.

1900. **Packard, A. S.** A new fossil crab from the Miocene greensand bed of Gay Head, Marthas Vineyard, with remarks on the phylogeny of the genus *Cancer:* Proc. Am. Acad. Arts and Sci., **36**, pp. 1–9.

Describes a new fossil crab, *Cancer proavitus.*

1900. **Woodworth, J. B.** Glacial origin of older Pleistocene in Gay Head cliffs with note on a fossil horse of that section: Bull. Geol. Soc. Amer., **11**, 455–460. Abstract in Science, new ser., **11**, p. 102.

Summarizes the evidence that the older Pleistocene bed is of glacial origin. Correlates it with the Columbia because of its stratigraphic position and lithologic character. Announces the finding of an astragalus of a horse in beds supposed to be Miocene.

1902. **Hollick, C. Arthur.** Geological and botanical notes, Cape Cod and Chappaquiddick Island, Mass.: Bull. New York Bot. Garden, **2**, pp. 381–407.

Includes observations on the topography, glacial deposits, and fossils of Chappaquiddick Island. The fossils consist of fragments of mollusks and plants found in the drift. The plants include several well-known Cretaceous species. The mollusks are not of the same age as those found at other places, but, according to Grabau, are probably more recent. Includes a list of the fossil plants, with descriptions.

1903. Fuller, M. L., and Veatch, A. C. Results of the resurvey of Long Island, New York: Science, new ser., **18**, pp. 729–731.

1903. Ries, Heinrich. The clays of the United States east of the Mississippi River: U. S. Geol. Survey, Prof. Paper 11, pp. 150–151.

A summary of the economic value of the clays of Marthas Vineyard. Concludes that the Cretaceous clays are of little value because they occur in highly folded beds. The glacial clays, which warp in burning, are not well adapted to brick making.

1903. Veatch, A. C. Notes on the geology of Long Island: Science, new ser., **18**, pp. 213, 214.

1903. ————. The diversity of the glacial period on Long Island: Jour. Geology, **11**, pp. 762–776.

These two papers by Veatch and that prepared by him in conjunction with Fuller bring out the following points: 1, That the Cretaceous deposits of the New England islands generally form the cores of what had been considered morainal ridges; 2, that there are few, if any, Tertiary beds on Long Island; 3, that several separate ice advances, with corresponding interglacial intervals, occurred in Pleistocene time; 4, that the older beds were folded by the action of ice; 5, that the topography of the last interglacial interval can still be recognized, and that the Wisconsin deposits are thin.

1904. Cushman, J. A. Miocene barnacles from Gay Head, Mass., with notes on *Balanus proteus* Conrad: Am. Geologist, **34**, pp. 293–296.

Barnacles found in connection with the fossil crabs referred to *Balanus concavus*.

1905. Brown, T. C. A new lower Tertiary fauna from Chappaquiddick Island, Marthas Vineyard: Am. Jour. Sci., 4th ser., **20**, pp. 229–238. Abstract in Science, new ser., **21**, pp. 990–991.

Gives results of a study of the mollusks that Hollick regarded as post-Cretaceous and classifies them as Eocene. Describes the species as new and different from the fauna of the Atlantic slope.

1905. Cushman, J. A. Fossil crabs of the Gay Head Miocene: Am. Naturalist, **39**, pp. 381–390.

Notes the occurrence of concretions in the greensand and describes the fossil crabs found in these concretions as well as two genera found in other material collected at Gay Head. A plate shows a restoration of *Archaeophax signifera*.

1906. Clapp, F. G. Evidences of several glacial and interglacial stages in northeastern New England: Science, new ser., **24**, pp. 499–501.

1906. Fuller, M. L. Clays of Cape Cod, Mass.: Bull. U. S. Geol. Survey No. 285, pp. 432–441.

Correlates on lithologic grounds the clay deposits of Cape Cod with those of Long Island.

1906. ————. Glacial stages in southeastern New England and vicinity: Science, new ser., **24**, pp. 467–469.

Announces a scheme for the differentiation of the Pleistocene deposits of Long Island and southeastern Massachusetts. Finds eight distinct epochs of deposition, four of which were glacial, and two well-defined long epochs of subaerial erosion.

1906. Hollick, C. Arthur. The Cretaceous flora of southern New York and New England: U. S. Geol. Survey Mon. 50, 219 pp.

Reviews the progress of geologic investigation of the Cretaceous deposits of the region, describes and correlates the plant-bearing beds, and gives systematic descriptions of the plant remains. Describes 222 species of fossil plants and figures many of them. Assigns part of the flora to the Raritan formation and part to the "Cliffwood formation" [Magothy] of the Cretaceous system of the Atlantic Coastal Plain.

1906. Veatch, A. C. Outlines of the geology of Long Island: U. S. Geol. Survey Prof. Paper 44, pp. 15–52.

The first complete account of the geology of Long Island, in which the author reiterates his previous conclusions. A very helpful paper in the interpretation of the geology of Marthas Vineyard, whose geologic features are similar to those of Long Island.

1906. Wilson, J. H. The glacial history of Nantucket and Cape Cod, with an argument for a fourth center of glacial dispersion in North America, 90 pp., New York, Columbia University Press. Abstract in Science, new ser., **23**, p. 389; Bull. Geol. Soc. America, **17**, pp. 710–711 (1907); Annals, New York Acad. Sci. **17**, pp. 624–625 (1907).

Summarizes, in two pages, the geology of Marthas Vineyard, and shows by diagrams the positions of the Wisconsin ice lobes.

1909. Bibbins, A. B. Occurrence of the Magothy formation on the Atlantic islands [abstract]: Science, new ser., **29**, p. 634; Bull. Geol. Soc. America, **20**, p. 672 (1910).

Concludes, from recent investigations, that the Magothy formation extends northward as far as Marthas Vineyard.

1910. ————————. Magothy formation of the Atlantic Coast [abstract]: Bull. Geol. Soc. America, **21**, p. 780.

1910. Jeffrey, E. C. A new *Prepinus* from Marthas Vineyard: Proc. Boston Soc. Nat. Hist., **34**, No. 10, pp. 333–338.

Describes a new species of fossil conifer from Gay Head.

1911. Wright, G. F. The ice age in North America, 5th ed., 763 pp. Oberlin, Ohio.

1914. Fuller, M. L. The geology of Long Island, N. Y.: U. S. Geol. Survey, Prof. Paper 82, 231 pp.

The most complete work on the geology of the northeastern part of the Atlantic Coastal Plain. Describes the same deposits that are found on Marthas Vineyard. Establishes the Pleistocene succession not only for Long Island but for Cape Cod and the other New England islands. Makes possible a satisfactory interpretation of the geology of Marthas Vineyard.

1915. Berry, E. W. The age of the Cretaceous flora of southern New York and New England: Jour. Geology, **23**, pp. 608 618.

Gives a brief review of the literature on the age of the Cretaceous beds in this region. Classifies the beds carrying Cretaceous fossil plants as Magothy. Finds no evidence of the Raritan formation east of Brooklyn.

1917. Allen, G. M. The whalebone whales of New England: Mem. Boston Soc. Nat. Hist., **8**, No. 2, pp. 282–285.

Describes the fossil bones found at Gay Head and refers some of them to one species. Notes the occurrence of fossils, and classifies them according to age. A plate shows some of the specimens.

1919. Fairchild, Herman L. Postglacial uplift of southern New England: Bull. Geol. Soc. America, **30**, pp. 597–636.

CHAPTER III

GEOLOGY OF NO MANS LAND

By J. B. Woodworth

LOCATION

No Mans Land is a small island of glacial drift that lies nearly due south of Gay Head light and about 4 miles south by west of Squibnocket Point, the southernmost part of Gay Head. The island rises above the submerged surface of a broad ridge that extends southward from Gay Head, as if it were a structural continuation of the island of Marthas Vineyard. The submarine contours of this ridge are shown on the charts of the U. S. Coast and Geodetic Survey[1] (See Plate 26). About halfway between the island and Gay Head two large rocks, known as Lone Rock and Old Man Rock, lie on shoals and are visible in the water from small vessels plying between Menemsha and the island.

GEOGRAPHIC FEATURES

No Mans Land has a maximum length of 1.6 miles from east to west and a maximum width of 1 mile from north to south. Owing to the existence of a small sandspit on its north coast and the incurving of its south coast toward its northwest point its average width is about half a mile. Its present area is somewhat less than 1 square mile. At a few places its surface rises to a height of 100 feet, but most of it lies below this level. The surface is decidedly undulating, consisting of knobs and hollows simulating the morainal deposits of many typical frontal moraines. The coast of the island on its east and south sides consists of steep cliffs of boulder clay, other clay, and sand, which are being rapidly worn away by the sea. The small sandspit that runs out near the middle of the island on its north side encloses a little lagoon on its eastern flank. This sandspit appears to have been in nearly its present position in 1602, at the time of Gosnold's landing, but according to Brereton's account, the lagoon on the east side of the island was then larger, probably extending eastward behind a flying beach, which has been driven backward and inward with the retreat of the cliffs at the east end of the island. An old sea cliff, largely grassed over, may be seen on the north coast west of the sandspit.

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[1] See chart of Marthas Vineyard, No. 112, 1914, 1/80,000; also chart 1107, showing Southwest Shoal and neighboring waters.

The island is now treeless, but it was forested when Europeans first visited it. Its surface is strewn with glacial boulders, and the hollows contain small swamps and beds of peat. In 1915–16 a single farmhouse stood back of the sandspit, and a few fishing stages or temporary huts on the cliff were being taken down. The present proprietor of the island has constructed, on the west side of the sandspit, a breakwater suitable for the protection of a small yacht. During recent years the island appears to have been used chiefly for grazing sheep.

DESCRIPTIVE GEOLOGY

Earlier Investigations

Owing to the inaccessibility of the island it has seldom been visited by geologists. It appears not to have been examined during the first State survey, made under Edward Hitchcock. It was referred to by Wright[1] as the "extreme terminal moraine," but it was first described by Shaler in his report on the geology of Marthas Vineyard, published in 1888,[2] which contained a geological map of the surficial Pleistocene deposits.

Shaler found that the island consists wholly of glacial drift. He recognized a lower till or boulder bed, which was overlain by beds of blue clay. Above a series of beds of fine sand and gravel he found another bed of till, which was capped in turn by deposits of gravel that he compared with kames. Much of this surface material, as he noted, "seems to have been shoved about in the forward movement of the ice in front of which it was formed."

The authors visited the island on September 11, 1915, and again on June 14, 1916, in company with W. C. Alden, of the U. S. Geological Survey.

A walk eastward around the beach of the island from the landing place on its north side affords an excellent view of the complicated structure of the folded beds in the cliffs and shows that the form of the surface is independent of the stratigraphy of the island. This surface truncates formation after formation from point to point about the island. It shows striking morainal relief in its hollows and hillocks, but these, like those of the central submarginal moraine on Nantucket, are the effects of the corrugation of an older surface of erosion, which cuts across the underlying Pleistocene deposits.

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[1] Wright, G. F., The Ice Age in North America, p. 123, New York, 1891. (Contains reference to earlier publications.)

[2] Shaler, N. W., Report on the geology of Marthas Vineyard, Seventh Ann. Rept., U. S. Geol. Survey, pp. 352-353, fig. 63, 1888.

Pre-Wisconsin Deposits

The deposits in the cliffs may be separated into stratigraphic units below the uppermost beds of gravel and sand, which are the "kames" described by Shaler. These beds, however, are remnants of the Hempstead gravel, which overlies the Montauk till. The Montauk till is strikingly displayed and contains boulders, the largest 6 feet across. This till is hard and compact and withstands erosion so well that in places it forms projecting buttresses in the face of the cliffs (See Plate **27**, fig. 2). In a part of the cliffs that faces southwest two beds of such till and intervening deposits of stratified sand and clay may be seen (Plate **28**, fig. 1), but here there may be some duplication by overthrust. The Gardiners clay is well exhibited at several places. At one place on the south coast (see Plate **27**, fig. 1), the Gardiners clay, as seen in 1915 and 1916, rested on a boulder clay, evidently the lower till mentioned in Shaler's report of 1888. This till bed beneath the Gardiners clay should be compared with the section at Nashaquitsa, where a similar bouldery bed (the Moshup till) has been exposed for several years in an upturned position, apparently unconformably below the Gardiners clay. (See fig. 18, and Plate **23**, fig. 1). The till at both these places seems to replace the Jameco gravel as the foundation on which the Gardiners clay rests. The accompanying plate (Plate **27**, fig. 1), reproduced from a photograph taken in 1916, gives an imperfect view of the contorted beds.

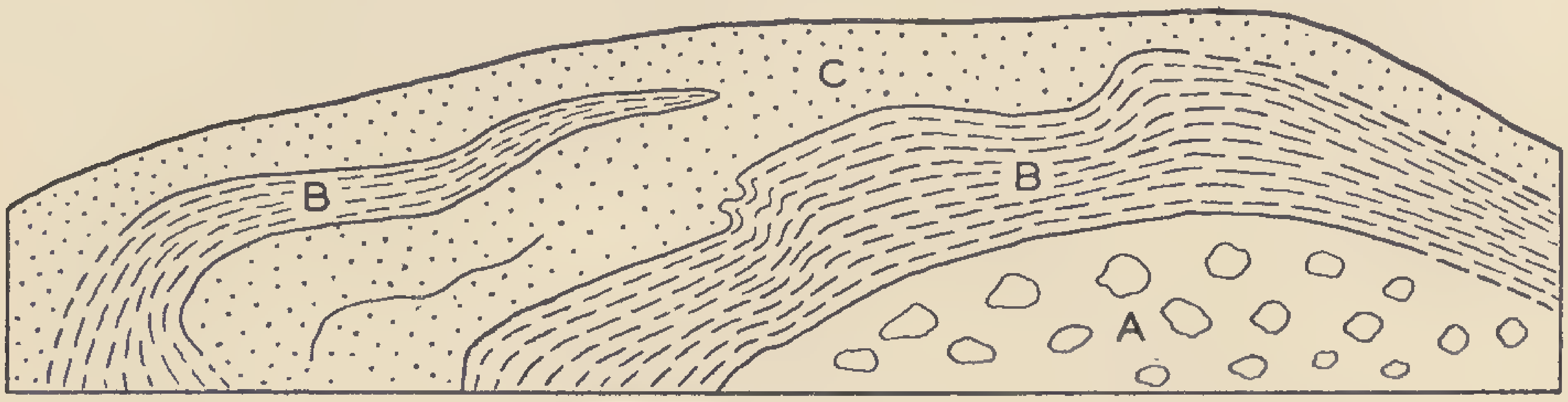

Fig. 18.— Contorted Pleistocene beds on the east coast of No Mans Land. A, Moshup till member, 10 feet thick, exposed above the beach; B, laminated blue Gardiners clay; C, sand, apparently at the horizon of the Jacob sand. The Moshup till is regarded as a till phase of the uppermost part of the Jameco gravel.

The cliffs reveal considerable diversity in the direction in which the contorted beds are overturned. Many small folds in the upper part of the section display what appears to be overthrusting to the south or to the west.

As the corrugated surface of the island truncates all the formations exposed in the cliffs along its coast, that surface should be regarded as a product of the erosion of the area since the latest pre-Wisconsin deposit was laid down. As stated above, the highest beds recognized in the cliffs are the deposits of the Hempstead gravel, which overlies the Montauk till. In this respect the surface corresponds in date with that of Marthas Vineyard during the Vineyard interval. The relation of the peculiar wrinkling of the surface, the pits, and the mounds to the underlying structure is more clearly shown here than on any other island in the group. This peculiar configuration may perhaps be a result of the action of the ice sheet of the earlier Wisconsin advance. What part of the deformation of the surface should be attributed to shoving, as suggested by Shaler in 1888, and what part to the differential settling of the underlying deposits is hard to determine, for some parts of those deposits consist mainly of clay and others mainly of sand or boulders.

Wisconsin Drift

The correlation of the upper, highly folded bouldery bed with the Montauk till and of the overlying beds of sand and gravel with the Hempstead member leaves little or no drift to be referred to the Wisconsin ice sheet. A rubbly layer a few inches thick forms the subsoil, and numerous boulders are scattered over the surface, but their origin is not certainly known. (See Plate **28**, fig. 2.) It seems as reasonable to suppose that they were left on the surface after the erosion of the contorted beds of boulder clay of the older Pleistocene, as to refer them to the more recent Wisconsin ice sheet. To those who, considering only what may be seen on this island, would hold that all these beds of till are of Wisconsin age, the problem seems very simple; but when we attempt to correlate the formations and the nature of the surface with clearly equivalent phenomena on a larger area, such as Marthas Vineyard, we see that the details of the topography worked out on the folded beds prior to the deposition of the Wisconsin moraine on that island indicate that the entire series of folded beds belong to periods long anterior to the time of the deposition of the surficial glacial drift of the mainland to the north.

The front of the Wisconsin ice sheet may have extended many miles beyond No Mans Land. The deposits that have been called the Montauk till and the Moshup till (the Moshup underlying the Gardiners clay and locally replacing the Jameco gravel) likewise are products of ice advances that extended beyond the present island. The broad submarine ridge on which the island stands may be a morainal accumulation piled up by deposition and displacement in more than one advance of the ice to this part of the coastal plain.

The boulders and pebbles on the beaches are commingled derivatives from the Moshup till, from the Montauk till, and possibly from the Wisconsin deposits. No reliable conclusions can be drawn from these erratics regarding the general drift of rocks at any one ice invasion. These materials may have been brought to the island during several successive stages. Among the pebbles on the beaches there were seen red felsite like that which crops out in the Carboniferous area from South Attleboro northward toward North Attleboro; gray Carboniferous conglomerate; red sandstone of the Carboniferous type seen in North Attleboro; gray Carboniferous sandstone, probably from the northern part of the Narragansett Bay region; porphyritic granite; gneiss; black schist, probably from the western part of the Narragansett Bay region; and quartzite. One slab of the red Cretaceous sandstone was seen. This fragment must have been dragged out of Cretaceous beds that lay between the island and the eastern entrance to Narragansett Bay. A piece of greenish-white slaty quartzite, resembling certain rocks in the Blackstone valley was also seen.

Marine Action

The eastern and southern coasts are evidently in rapid retreat. The north coast west of the sandspit appears to have become largely covered with vegetation owing to a cessation of the attack of the waves and currents on that side — an attack which apparently went on when the island was larger and its shape different. Unfortunately no accurate charts of the island are available to permit a comparison of the old coast line with the present and to show the rate of loss of land. The boulders derived from the beds of till greatly retard the retreat of the cliffs and account in part for the preservation of this small island to the present day.

CHAPTER IV

GEOLOGY OF BLOCK ISLAND

By J. B. Woodworth

HISTORY AND GEOGRAPHY

Block Island, or New Shoreham, lies off the coast of Rhode Island, from 10 to 16 miles southwest-by-south of Point Judith. Its southwest point is about 15 miles northeast of Montauk Point, on Long Island, and its eastern coast is about 37 miles west by south of Gay Head, the western extremity of Marthas Vineyard. The island is about 6 miles long from northeast to southwest and in its southern broader part is about 4½ miles wide from east to west. (See Plate **29**.)

Block Island was known to the aborigines as Manisses, a name preserved in Whittier's poem on the wreck of the Palatine. Verazzano gave the island the name of Claudia in 1624, as certain early maps testify. After the island was explored by Adrian Block, the Dutch navigator who visited this coast in 1614, the name Adrian's Eyland was placed for a time on Dutch maps. Later the surname of the old navigator became the name of the island. In 1672 a town charter granted to the island by the Rhode Island Assembly provided that the ''said town of Block Island . . . shall be called New Shoreham, otherwise Block Island.'' The English village name, New Shoreham, which appears in numerous records and on maps of the island, attests the English settlement of an island that once lay within the territory of the Netherlands in the New World.

As the English settlement of the island was followed by certain changes in its features and life that are related to the surficial geology and to certain geological conditions that are now in part effaced, it seems well to relate briefly the history of the island.

When Endicott's expedition visited Block Island in September, 1636, it ''was all overgrown with brushwood of oak,'' according to Winthrop's History of New England, but there was no good timber on it. Winthrop reports that the island was said to be about 10 miles long and 4 miles broad, and full of small hills. We may safely assume that the length thus given was too great, even if we make allowance for the loss of the small island at Sandy Point, on the north shore, and for the retreat of the cliffs on the south shore. In the 280 years since this estimate was made, the south shore, if we assume that it has retreated 3 feet a year, would have stood about 900 feet south of the present Mohegan

Bluffs. Undoubtedly the island has been greatly reduced in size since the sea reached its present attitude to the land, a few thousand years ago.

The casual visitor to Block Island is at once impressed by the almost complete absence of trees. Here and there groups of trees planted about houses appear to enjoy protection from the buildings rather than to shield them from the wind. These trees were planted in an attempt to restore a condition that existed long ago. When the island was discovered it was evidently clothed with a forest that afforded timber and wood to its first settlers. Its deforestation was a consequence of over-population. The early records mention the forest and give certain details concerning it, and the remains of trees found in swamps prove its former existence.

In his ''history of Block Island,'' Livermore,[1] to whom we are indebted for much information concerning it, tells of a tradition of the forest, that had been retained in the memory of the inhabitants as late as 1877, and his research in documents concerning the inhabitants disclosed several instructive particulars concerning the vanished forest. Thus, the inventory of Robert Guthrige's estate in 1692 mentions ''forty-two acres in the west woods at 20 shillings per acre.'' According to Livermore, local regulations made in the first quarter of the eighteenth century indicated a growing scarcity of trees available for use as timber and fuel. By the year 1750, however, the use of small glacial erratics for the construction of stone fences and of peat taken from local beds for fuel relieved the anxiety of the inhabitants concerning their vanishing forests. From this time onward, at least, wood for constructing houses and boats was brought from the neighboring mainland.

Thus the destruction of the native forest led to the removal of the glacial boulders from the field and to their incorporation in the remarkable network of stone fences that now divides the farms. (See Plate **31**, fig. 1.) A writer has estimated that there are about 300 miles of such stone fences, an estimate which affords some idea of the number or quantity of glacial boulders that were once scattered over the surface. The forest appears to have been destroyed mainly by the quest for fuel. Peat, locally called ''tug,'' was not used until 1721, but its use became general about 1750 and it remained the chief fuel used on the island for fully a century.

The history of the forest is paralleled by that of the aborigines. From a native population of about 1,000 in 1662, the date of the English settlement on the island, the number of Indians had dwindled to 51 in 1774, and a century later only a single survivor of the race was alive. An occasional stone arrow or celt found in the soil of the island is now the only witness of their one-time lordship.

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[1] Livermore, S. T., History of Block Island, Hartford, Conn., 1877. I am indebted to this book for several notes on the history and condition of the island in past times, as well as for references to changes which are not apparent to the casual explorer of the island.— J. B. W.

In addition to the map that accompanies this report (Plate 29) there is available for reference a large-scale map published by the U. S. Coast and Geodetic Survey, which shows the topographic features of the island in great detail.[1] Were it not for the cordons of beaches and strips of marsh land that connect the several parts of Block Island, it would appear on the map as two larger and several much smaller islands. The northern part of the island, known as "Corn Neck" or "The Neck," rises gently from the western coast to the steep bluffs of Clay Head and Balls Point, on the east coast. This part of the island is extended into the waters of the Sound by a sandspit of recent formation, known as Sandy Point. A dangerous shoal lies farther north, on the site of an isle that disappeared within historic time.

The main southern part of the island, including the highest elevation, Beacon Hill, which reaches an altitude of 210 feet above mean sea level, ends abruptly on the south coast in steep cliffs, 110 to 150 feet high, known as Mohegan Bluffs, a wall of boulder clay, other clay and sand, which, from the ravages of sea waves below and rainfall above, displays fallen masses or the gullied slopes of mountains in miniature. The boulder-strewn beach at the base of these bluffs is one of the most desolate tracts on the eastern coast of the United States, an ever-changing ragged coast, the terror of shipwrecked mariners and the despair of the owners of the land along the brink, who from time to time witness the fall of their land into the sea.

GEOLOGY

The formations exposed above sea level in the cliffs of Block Island consist of beds of gravel, boulder-clay, other clay and sand, ranging in age from Upper Cretaceous to and through Pleistocene. The glacial deposits include boulders of granite and gneiss derived from the ancient crystalline rocks of the adjoining mainland. The formations that lie below sea level near the island and the mainland probably include several hundred feet of beds of Cretaceous clay and sand, which lie upon the seaward sloping surface of a basement of ancient crystalline rocks.

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[1] U. S. Coast and Geodetic Survey, Chart 356, scale 1/10,000.

Pre-Cretaceous Basement

The thickness of the unconsolidated material that lies upon the crystalline basement rocks is unknown. The only available method of determining the depth of this basement below the level of the sea is to project beneath the island the average slope of the remnants of an old surface of these rocks from the south coast of the mainland. This surface dips about 20° south of east at the rate of about 30 feet to the mile, whence it is presumed that the bedrock lies about 540 feet below sea level under the north end of the island, and about 810 feet below it under the south end. This estimate, however, takes no account of valleys in the surface of the bedrock; it indicates only the general depth. Faulting along the coast or warping of the ancient rock surface may increase considerably this estimate of the depth.

The rocks of this crystalline basement, so far as they can be determined by observing the crystalline rocks on the neighboring mainland, consist of gneisses, schists, and later granitic intrusives of Carboniferous age or older. The coal beds of the southern extension of the Narragansett coal field should lie at similar depths between 10 and 30 miles east of Block Island, under a cover of Cretaceous sand and clay, upon which lie glacial deposits.

Upper Cretaceous Deposits

CHARACTER AND DISTRIBUTION

The beds of light clay and of dark lignitic Upper Cretaceous clay, found under most of the islands off the south coast of New England, crop out in small exposures as beds of white clay on the east coast of the island and at Clay Head, on the north coast, and as dark lignitic clay at a place back of the beach near Old Harbor, in the southern part of the island. Nodules containing the leaves of Cretaceous plants have been found in the glacial drift, showing that they were derived from Cretaceous beds that lay far north of the site of the island.

THE WHITE CLAY

The beds of kaolinite, or white clay, and the associated beds of white quartz gravel that are folded in with beds of glacial sand and gravel in the cliffs at Clay Head contain no fossils but are presumably like the neighboring beds of lignitic clay found at the horizon of the Magothy formation in the lower part of the Upper Cretaceous series. These beds are found at but few places, and as all the beds on Block Island are greatly contorted little can be said of their stratigraphy or their probable extension from the cliffs into the interior of the island. The beds of clay seen in Clay Head probably extend for some distance back from the cliffs beneath the thick beds of gravel and boulders, but the complex interfolding of the beds of Cretaceous clay with beds of glacial sand and gravel prevents any reliable theoretical projection of the underground structure.

The higher marine Cretaceous beds that are found on Marthas Vineyard and in New Jersey, as well as the Tertiary beds seen in the cliffs at Gay Head on Marthas Vineyard, are not found on Block Island. This series of beds probably suffered much erosion in this region during pre-glacial time.

THE LIGNITIC CLAY

Beds of lignitic clay are exposed, though poorly, beneath a coating of till in the low cliff at Old Harbor. Some years ago, when they were better exposed than they are now, the beds showed anticlinal structure, being much crumpled on their northern limb. The beds cropped out for about 100 feet along the shore. The anticlinal fold contained a layer of friable lignite 6 inches thick. In the northern crumpled part of the section a nearly vertical bed, 3 feet thick, was then seen. Chunks of lignite showing the structure of wood are occasionally found in this cliff. Overlying the bed of dark clay there were beds of sandy clay, which were in places cemented so as to form a reddish, micaceous argillaceous sandstone resembling the fragments of drift found in the overlying Pleistocene formations. Livermore[1] states that a substance which appears to have been lignite was found in dredging the harbor many years ago. Beds of lignitic clay and of white kaolinite like that seen in the bluffs at Clay Head probably underlie the island not far below sea-level.

FOSSIL FLORA

Hollick[2] has collected from the drifted fragments of Upper Cretaceous beds found in the Pleistocene deposits of the island a dozen species of plants, viz.:

Gleichenia gracilis Heer. (Plate I, fig. 9.)
Protophyllocladus subintegrifolius (Lesq.) Berry (Plate V, figs. 1–6).
Dammara minor n. sp. (Plate II, figs. 35–37.)
Ficus Krausiana Heer. (Plate X, figs. 1–3.)
Magnolia woodbridgensis Hollick. (Plate XX, fig. 7.)
Laurus plutonia Heer. (Plate XXVIII, figs. 1–2.)

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[1] Livermore, *op. cit.*, p. 155.

[2] Hollick, Arthur, The Cretaceous flora of southern New York and New England, U. S. Geol. Survey, Mon. 50, 1906. (See tables on pages 120-128 and the plates and figures indicated in the list.)

Celastrophyllum grandifolium Newb? (Plate XXXIII, fig. 8.)
Eucalyptus nervosa Newb. (Plate XXXV, fig. 16.)
Eucalyptus Geinitzi Heer. (Plate XXXV, figs, 1–8; 10–12.)
Tricalycites papyraceus Newb. (Plate V, figs. 8–12.)
Widdringtonites subtilis Heer. (Plate IV, figs. 2–5.)
Cyparissidium gracile Heer? (Plate III, fig. 11.)

This flora includes ferns (*Gleichenia*), coniferous trees (*Protophyllocladus, Dammara, Widdringtonites, Cyparissidum*), fig-trees (*Ficus*), the magnolia, a laurel (*Laurus*), probably two species of eucalyptus, a shrub related to the bitter-sweet (*Celastrophyllum*), and plant remains of doubtful affinities (*Trycalycites*). This flora indicates a mild, temperate climate, more like that of the Carolinas today than the present climate of southern New England. These plant remains are not marine, but were laid down on a coastal plain like that now seen farther south. This plain extended along the southern coast of New England, reaching for an unknown distance out toward the edge of the present continental shelf and spreading inland over the ancient crystalline rocks of the present mainland. Meandering streams charged with the products of the weathering of the crystalline and other hard rocks of the interior, already much worn down by erosion, slowly built up a vast plain along a smaller Atlantic basin than that of the present day. Soon after these plant-bearing beds were deposited the land sank beneath the sea or the sea rose upon the land and marine beds were laid down, but these beds have not been found on Block Island.

Tertiary Material in Pleistocene Glacial Drift

Deposits of the Tertiary system, comprising the Eocene, Oligocene, Miocene (known on Gay Head), and Pliocene series (found at Gay Head and on Long Island) have not been found on Block Island. Tertiary deposits are to be sought along the line of contact between the upper surface of the Cretaceous beds and the base of the Pleistocene or glacial deposits. This line at Clay Head clearly marks an unconformity between the Pleistocene and the Cretaceous.

MIOCENE BOULDER

The existence of Miocene deposits on Block Island prior to the glacial epoch is indicated by a fossiliferous boulder found by W. O. Crosby on the beach near Clay Head, though possibly this boulder may have been brought to the beach by some boat.[1]

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[1] Shimer, H. W., Fossiliferous Miocene boulders from Block Island, R. I., Am. Jour. Sci., **41**, pp. 255-256, 1916.

EOCENE MATERIAL IN RECENT WRECKAGE

Fossiliferous phosphatic pebbles from a formation having no counterpart in New England were left on the beach near Southwest Point on July 17, 1877, by the wreck of the schooner *William S. Skull*, bound from Port Royal to Vineyard Haven. These pebbles, which are light yellow, rather porous, and contain numerous cavities from which shells had been weathered out, were at first thought to be peculiar to some Miocene formation not exposed on the island, but inquiry proved that they came from the Eocene Cooper marl of South Carolina.[1]

Coal often washes ashore from wrecks on or near the coast of Block Island, and some pieces of crystalline rock foreign to southern New England may have been carried to the beaches of the island from wrecks such as that of the barkentine *Alexander Campbell*, laden with paving blocks from Maine, which sank 7 miles southwest of Block Island on November 27, 1888.

Pleistocene Formations

CLASSIFICATION

Everywhere except along the strand and in the marshes Pleistocene or glacial formations make up the great mass of Block Island, forming its surface material, entering into its soil, and constituting its subsoil. These formations are exposed in the Mohegan Bluffs, on the south coast, and at Clay Head, on the northeast coast. They were early recognized as mainly of glacial origin and, together with the surface boulders, were indicated on geological maps as part of the terminal moraine that is traceable from Nantucket westward across Marthas Vineyard to Long Island and thence far into the interior of the Continent. Later geologic work showed that the glacial deposits of the island are divisible into several beds of boulders, gravel, sand, and clay, and that the surfaces of these beds show traces of old land forms that were in their time as distinct as the present surface of the island.

All the boulders, cobbles, pebbles, and granitic sands of the island except the Cretaceous fragments already described appear to have been carried from the mainland on the north, several varieties of rock having been identified with those of ledges that lie as far north as Cumberland, R. I., and George's Hill, in Leominster, Mass., The succession of glacial events has been set forth in the introductory chapters of this report. What is here stated concerning them presents more local detail. The succession of deposits is shown in the following list:

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[1] Dall, W. H. On the "land phosphate" of the Ashley River district, South Carolina, Am. Jour. Sci., **48**, pp. 300–301, 1884.

Wisconsin till
Submarginal ground moraine of Nantucket substage
Vineyard erosion interval or interglacial stage
Manhasset formation:
    Hempstead gravel member
    Montauk till member
    Herod gravel member
Jacob sand
Gardiners clay
Jameco gravel
Post-Mannetto unconformity
Weyquosque formation
Dukes boulder bed

CHARACTER OF THE FORMATIONS

The Dukes boulder bed consists of waterworn, rearranged, partly cemented boulders and stones found on Block Island only at Clay Head. The type locality of this bed is at Gay Head, Marthas Vineyard.

The post-Manetto unconformity is an irregular surface of contact between the beds just described and the overlying Pleistocene formations. This incongruity is shown on Block Island at Clay Head, on Corn Neck, but is well displayed at Gay Head, on Marthas Vineyard.

The Jameco gravel is glacial outwash that in places carries boulders at its base, if it has been correctly identified at Clay Head. It is believed to be the product of glaciation that profoundly disturbed and folded the older Pleistocene and Cretaceous beds at Clay Head.

The Gardiners clay is typically displayed on Gardiners Island, where it carries marine fossils in its lower part. The beds are extensively exposed in the lower part of Mohegan bluffs, on Block Island.

The Jacob sand is nearly everywhere a fine sand composed of grains of quartz, feldspar, and other minerals, such as are produced by the levigation of glacial material by off-shore waves or gentle currents. In places, beds of fine gravel lie at the base of the formation.

The Manhasset formation consists of glacial gravel below, known as the Herod gravel member, followed above by a very thick bed of boulder clay (the Montauk till member), which in places on Block Island forms two beds separated by beds of gravel. Upon the Montauk lie the gravel and sand of the Hempstead member, less well preserved on the island as the result of their erosion.

The Vineyard interval was an epoch of stream erosion prior to the advent of the last or Wisconsin ice sheet, during which the island was considerably modified in contour.

The Wisconsin stage of glaciation is represented by the surface boulders and rubbly till seen in the tops of the bluffs and by a peculiar rolling topography that masks the stream lines of the Vineyard erosion interval except where those features were strongly developed. Eskers, true kames, and typical frontal moraines are wanting on the island.

The distribution of these deposits is described in the text on Clay Head and the Mohegan bluffs, where they form the chief features in the coastal scenery.

BASAL PLEISTOCENE OF THE CLAY HEAD SECTION

The oldest Pleistocene on the island is exposed in the sea cliff at Clay Head. In the summer of 1892 the section showed two overturned folds of the beds of white clay containing granitic gravel and sand, infolded in synclines.[1] The deposits were regarded as Pleistocene because of the fresh feldspar they contained and their lithological similarity to other beds of gravel of glacial origin, either in the kames, eskers, and sand plains of the mainland or, reworked by the sea, on existing beaches. No Tertiary deposits were seen between the Pleistocene and the Cretaceous beds.

In the summers of 1915 and 1916 the cliff at Clay Head had worn back considerably and the beds, being comparatively free from talus, were much better exposed than in 1892. The infolded oldest Pleistocene beds exposed in clear relations to the Cretaceous deposits consist of fine sandy gravel composed of subangular bits of feldspar-bearing rocks and quartz of vein origin, derived from the mainland, along with reddish felsite — an assemblage indicating an origin from the region about eastern Rhode Island and the adjacent part of Massachusetts as far northeast as the town of Attleboro, where red felsitic rocks now crop out. Part of the granitic pebbles are somewhat decomposed and the entire deposit has a peculiar drab color, which recalls the lower sand beds at the base of the Pleistocene in Nashaquitsa and Gay Head cliffs, on Marthas Vineyard. In the region to the east this drab color is usually associated with oxidized and hydrated glauconite or greensand derived from the subjacent Miocene beds, and it probably has the same significance at Clay Head. At least four closely appressed overturned synclines inclosing beds of these gravelly sands were exposed between similarly overturned anticlines of Cretaceous beds. The isoclinal structure has a northerly dip of about 45°, and the bottoms of the synclines, or their turns, were not exposed above the beach. In 1892 the bottom turn of a syncline then exposed stood a few feet above the beach. It appears that as the cliff retreats these folds, which dip steeply inward, carry their inferior turns below sea level. The beds may have been overthrust on each fold, but they are so greatly crushed as to prevent a satisfactory determination of details as well as of thickness. No traces of fossils were seen.

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[1] Woodworth, J. B., Unconformities of Marthas Vineyard and Block Island, Bull. Geol. Soc. Am., **8**, 1897, pp. 197–212. (See fig. 3, p. 210.)

A mass of rather consolidated gravel and boulders, which appears to be an extension of the gravel bed shown in the syncline figured by Woodworth[1] in 1897 was exposed here in 1915. This mass as now exposed is a boulder bed of glacial origin. It lies in such a position that it may be interpreted as a basal bed in the syncline in which it is evidently infolded. It shows a gradation from large boulders at the bottom to gravel at the top, upon which lies finer gravel and sand. The bed contains numerous ironstone concretions derived from the Cretaceous formations and small boulders of hardened drab clay derived from near-by deposits. This bed has evidently been eroded by an ice sheet, but practically every stone is waterworn, as if it had been exposed to the action of sea waves. Similar boulder beds are involved in the early highly folded deposits at Gay Head. This bed may be modified drift of the earliest ice advance, a local deposit at the base of the Pleistocene deposits. It is older than the Gardiners clay, the Jameco gravel, and the icesheet whose thrust folded the beds that included these early Pleistocene deposits. It is the local representative of the Dukes boulder bed.

A few rods north of the section just described the blue Gardiners clay may be seen in an anticline, but its contact with the highly folded mass is not exposed. Perhaps it may be wrapped unconformably around an uplift composed of the highly folded beds of the older series. The more significant part of the section, so far as it could be understood in 1915 and 1916, is shown in fig. 19. The section is not less important in the investigation of the first glacial invasion in southern New England than that at Gay Head cliffs. It should be examined from year to year as Clay Head is cut back by the sea, and the parts now covered by a deep talus are exposed to view, in order to obtain a more complete record of an obscure group of deposits, which have been seen only at three or four places in the New England Islands.

The beds of boulders, gravel, and sand that lie north of the overturned

[1] *Op. cit.*

folds rest unconformably upon them, and the upper boulder bed, which is probably of Wisconsin age, extends over beds of sand and clay that lie upon gravel of the same age as that on which these supposed Wisconsin boulders rest in areas farther south. These beds of sand and clay are older than the Gardiners clay and the overlying Jacob sand and Manhasset formation, which come into view still further north in unmistakable character and which have nothing in common with the beds here considered. On the other hand, although the Manetto stony blue clay till of the Gay Head section has not been recognized in the folded beds at Clay Head, it may antedate the strong overturning shown at Clay Head, as it does at Gay Head, and the overturning, the erosion of the folds, and the consequent unconformity may be of the same age in both sections. As the folded beds in the section at Clay Head lie below the horizon of the Gardiners clay and do not include the Jameco gravel, the sand and gravel of the beds lettered E and F in fig. 19 may represent the Jameco formation, at the base of which is a glacial bouldery deposit not shown so well elsewhere.

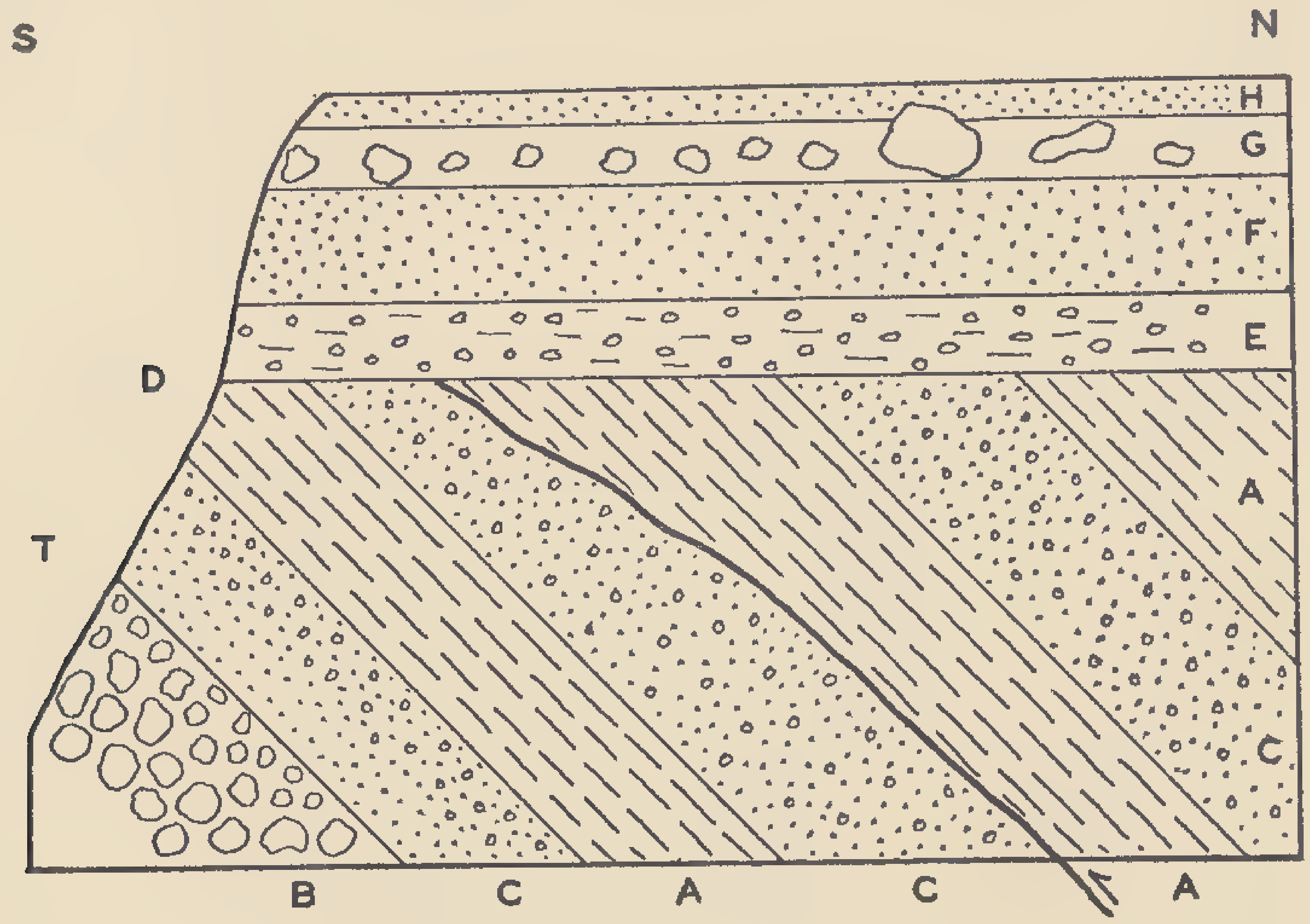

FIG. 19.— Cross section of Clay Head in 1916, showing overturned compressed anticlines or isoclines accompanied by overthrust. *A*. Upper Cretaceous white clay; *B*, Dukes boulder-bed; *C*, Weyquosque formation (gravel and drab sand); *D*, unconformity (post-Mannetto interval); *E*, bouldery gravel; *F*, glacial sand; *G*, Wisconsin (?) bouldery drift; *H*, subsoil of sand and clay. The beds lettered *E* and *F* probably represent the Jameco formation.

Just north of the Clay Head folds there is a broad anticline in which the

Gardiners clay, seen in the axis, is overlain by the Jacob sand, which is in places contorted. About three feet of fine glacial gravel, which rests on the Gardiners clay, forms the base of the Jacob sand in this anticline, so that the sand there is not a transitional deposit.

On the northern gently sloping limb of this anticline an excellent exposure of the succession above the Jacob sand was seen in 1916. The overlying Herod gravel included a bed of stony unstratified blue clay or till. Above this glacial coarse material there is a bed of sand, which passes up into a bed of gravel about 20 feet thick, upon which lies a typical boulder clay containing a lenticular bed of gravel, the Montauk till. The surface cuts across this fold, which therefore antedates the pre-Wisconsin surface of erosion recognized on the island. The Montauk till also is folded down into the section just north of the Cretaceous exposures in Clay Head, and is there underlain by the Herod gravel in such manner as to raise the question whether the opinion that the Jameco gravel lies upon the Cretaceous folds should not be replaced by the opinion that the gravel lies at the Herod horizon. Certain details can be learned only after the slumped part of the cliffs, at the most critical position for exhibiting structural relations, has been cut back so as to afford fresh exposures.

South of the Clay Head section folded beds of sand, sandy clay, blue clay, and gravel were exposed in 1916, and south of a small valley that comes to the coast at that place there was exposed a section of bouldery gravel in a sandy and clayey matrix, overlain by about six feet of gray clay, the stratigraphic relations of which are not perfectly clear but which may be an extension of one of the beds seen farther north.

The Mohegan Bluff section.— Excellent exposures of the older Pleistocene from the Gardiners clay up through the Jacob sand into the Manhasset formation, with its subdivisions of Herod gravel, Montauk till, and overlying Hempstead gravel, make up Mohegan Bluff (Plate **30**) at Southeast Point. The beds have been thrown into rather gentle folds. No overturned folds such as are seen at Gay Head in the older basal Pleistocene are commonly found in the middle Pleistocene.

VINEYARD INTERGLACIAL STAGE

A cursory examination of the summit line of the cliffs of the island reveals the fact that the beds of Montauk till and the associated beds of gravel (Herod and Hempstead members) of the Manhasset formation, which form the highest of the well-developed glacial deposits on the island, are everywhere truncated or eroded at the present surface, which bears a thin coating of till, some rubbly drift, and here and there beds of sand or clay, as well as embedded boulders, most of them presumably brought here during the last glacial invasion. An examination of the interior of the island gives some clue to the nature of this erosion prior to the last glacial stage, after the Manhasset beds were laid down, for the massive contours of the higher ground show traces of slopes and masked gullies running down in the manner of the vales left in incoherent strata by the action of running water. The structure of the Manhasset beds, as shown in the cliffs, particularly at Clay Head and north of Balls Point, indicates that the Wisconsin ice sheet deformed them and pushed up, at least to a certain extent, the highland on Corn Neck; but despite this action and the masking effect of the glacier upon the antecedent topography, there remains here and there the appearance of a land surface typical of the Vineyard interval, the full nature of which is well shown in the upland part of Marthas Vineyard.

The traces of old drainage lines are best seen around the northern slopes of Beacon Hill, especially on the northeast versant of the hill, where a well-defined groove widens out downward and the contours of stream work are slightly masked by subsequent glaciation. Over the greater part of the island all semblance of the sculpture accomplished by streams is entirely obliterated by glacial erosion and the deformative work of the Wisconsin ice sheet. (Plate 31, fig. 1.) Owing to this defacement of the pre-Wisconsin topography it is not possible to say whether the depression between the northern and southern parts of the island represents the depth of erosion during the Vineyard interval or whether it was made by the Wisconsin ice sheet.

The flattish areas in the southern part of the island north and west of Sands Pond, which stand at an elevation of about 120 feet and another area north of Fresh Pond, standing above 100 feet, appear to be remnants of a plain or terrace, which was probably larger during the Vineyard interval. Traces of a pre-Wisconsin surface at about this elevation (100 to 120 feet) are also found in the eastern part of Marthas Vineyard.

NANTUCKET MORAINE

CHARACTER AND EXTENT

Aside from the beaches and dunes along the coast and the marshes formed in the shallow, protected embayments, chiefly between the northern and southern parts of the island, the entire surface is covered with a thin mantle of bouldery drift of the Nantucket moraine of the Wisconsin stage of glaciation.

The glacial boulders and other drift of this sheet appear to be rather uniformly distributed over the island, the mounds, ridges, and hollows of the surface being possibly due in part to irregularities in the thickness of the drift but more likely to the effect of the deformation of the surface by the kneading of the incoherent largely clayey beds by the overriding ice. Neither in the alignment of these ridges and hollows nor of such boulders as have not been gathered into walls is there indication of any considerable frontal moraine. Such deposits, if formed at all, must have accumulated south of the present land area on a surface that has been cut away by the sea or that now lies below sea level. The surface of the island, which may be called a corrugated moraine, is very similar to that of the northern half of Nantucket, where this type of topography was developed half a mile to a mile or more back of the ice front. Therefore, although Block Island was moulded beneath the ice sheet in the manner described, the front of the ice at the time its surface was formed may have been 1 to 5 miles south of the existing south coast of the island.

The axes of the corrugated moraine of the island in Corn Neck, north of the central depression, extend nearly westward, but those in the main body of the island, farther south, particularly in its western half, trend southward. These features are brought out best by the detailed chart of the island published by the United States Coast and Geodetic Survey.[1]

The westward trend of the ridges and hollows on Corn Neck coincides with the trend of the axes of the folds seen in the cliffs at Balls Point. The beds in Mohegan Bluffs, on the south coast, show several rather gentle folds, which have axes nearly normal to the coast line and are essentially in agreement with the trend of the formations of the inland surface.

The corrugations on Corn Hill thus appear to be the effect of pressure acting from north to south, in the general direction of the motion of the ice. This direction is shown not only in the older folded beds below the Jameco formation but in the broadly folded Manhasset formation. The folding in the area south of the depression occupied by Great Salt Pond seems to have been produced by pressure acting from the east or west, and as this folding is more clearly shown in the west half of that area the pressure probably came from the west. This conclusion is borne out by some small folds in Mohegan Bluffs, which have been overturned toward the east. As Upham many years ago pointed out, Block Island lies in an interlobate position, in the axis between the Narragansett Bay lobe and a broad lobe on the west. The moraines near

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[1] U. S. Coast and Geodetic Survey, Chart No. 356, scale 1/10.000.

Exeter and Slocum, R. I., show that the interlobate axis lay about in longitude 71° 32′ W. when the ice front had retreated to that locality, and that the axis was but slightly west of that position on the west side of Point Judith when the ice front stood at the Charleston moraine, trending west of south, toward Block Island. Thus the push from the ice lobe moving over the island from Block Island Sound caused the topographic trend noted. The accentuated area lies west of a line skirting from north to south the west coast of Corn Neck, on which there are traces of a topographic trend from northwest to southeast, parallel to the western border of an ice lobe that issued from the Narragansett Bay depression.

A number of small shoals that lie off the south coast, where the bottom is from 12 to 14 fathoms deep, may be wave-levelled tracts of submerged frontal moraine. A shoal extends southwestward from Southwest Point to Southwest Ledge. It has a minimum depth of 4½ fathoms and the sea breaks on it in heavy weather. This shoal is produced by an extension of the glacial formations of the island toward Montauk Point; but the materials on Southwest Ledge may be largely pre-Wisconsin.[1]

GLACIAL BOULDERS

The surface of Block Island, according to all accounts, was originally thickly strewn with glacial erratics of all sizes. The largest boulder seen by the writer lies on the northern slope of Pilot Hill, about half a mile from its summit. As measured in 1893 it rose 6 feet above the surface of the ground and was 15 feet 10 inches across. About in the middle of the eighteenth century the scarcity of wood for fences, combined with the increase of agriculture, led to the clearing of the fields and the construction of stone fences. Many cartloads of stones that were too small for use in making fences were thrown into the kettles and hollows at the bottoms of the hills, so that only a few small tracts were left in something like their natural state.

The boulders on the surface of Block Island were perhaps brought to their present positions from the mainland by the Wisconsin ice sheet. Although these erratics were derived from the mainland, it is not certain that any particular boulder was carried to the island during the last ice invasion, for the erosion of the older folded boulder beds on the island suggests that boulders from these beds became commingled with the latest drift from the mainland. For this reason particularly it is impossible to determine whether the boulders and pebbles now on the beaches of the island were brought in during one ice advance or another, for the material in all the boulder beds and pebble beds is very similar, the chief difference being that many kinds of rocks in the older boulder beds are much disintegrated, although their disintegration is not everywhere apparent. Boulders found on the beaches, therefore, even if they certainly came from the cliffs, have little significance in determining the direction of movement or the ice sheet during any particular epoch. The following observations were made with this precaution in mind.

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[1] See U. S. Coast and Geodetic Survey Chart No. 1211 (Block Island Sound) July, 1912.

DIRECTION OF DRIFT SHOWN BY BOULDERS

Some boulders seen on Block Island can be traced to well-defined outcrops on the mainland.

CUMBERLANDITE BOULDERS

One of the most distinctive rocks of southeastern New England is the so-called Cumberland iron-ore or peridotite of northeastern Rhode Island. The distribution of boulders and fragments of this rock in areas south of its outcrop was described in 1893 by Shaler, who had not at that time extended his observations to Block Island. In August of that year a boulder of this rock weighing ten pounds was found on the shore of the island on the west side of the point on Mohegan Bluffs, south of Fresh Pond. Another boulder, 2 feet long, 18 inches wide, and 1 foot thick was found near by. The smaller of these two boulders may have been brought to the island by fishermen as ballast in a boat, but the larger boulder was probably not transported by human agency. Boulders of this rock are found as far east as Gay Head, on Marthas Vineyard. The boulders on Gay Head lie 30 miles east of the meridian passing through the place of their origin, but those found on Block Island lay scarcely 10 miles west of that meridian. As the ice moved, at least during the Wisconsin stage, nearly southward through Narragansett Bay, deploying lobewise to Block Island on the southwest and toward Gay Head on the southeast, with an axis of southward striation on the site of Newport, it is evident that Block Island lay well within the limit of the fan of erratics that were spread southward by the lobes of ice that moved at different times from the Narragansett Bay region.

Glacial striae on the west shore of Narragansett Bay north of Point Judith indicate the direction of transportation of drift to Block Island, as follows:

Narragansett Pier, on high granite bluff south of railroad terminus	S. 19° W.
Rose Hill, Wakefield, R. I.	S. 21° W.

Point Judith Neck, east shore, 1½ miles south of Narragansett Pier	S. 19° W. and S. 29° W.
Little Neck above the Narrows	S. 27° W.

These glacial striae at places examined in succession southward show an increasing trend westward, which is a normal result of the outward curvature of the lines of flowage of the bottom ice in a glacial lobe. The island bears between 15° and 37° west of south from Point Judith, and it came well within the reach of ice moving down the west side of Narragansett Bay and deploying as a lobe between Gay Head and the interlobate axis described above.

UPPER CAMBRIAN QUARTZITE PEBBLES

Waterworn fragments of an Upper Cambrian quartzite or sandstone containing small fossil branchiopods are found on the beaches of Block Island. Such fragments are found also in the Carboniferous conglomerate near Newport, R. I., as well as farther north, in the Rhode Island coal field. Walcott found some among the pebbles on the beach at Westerly, R. I.

AGATES

Fragments of impure or clouded or banded red and white agate are found on the beaches of the island, as well as in the oldest Pleistocene deposits at Clay Head. Some fragments as large as 6 inches in diameter have been seen on the beach south of Clay Head. Some pieces of this agate contain a trace of a reddish shaly country rock, which suggests that they were brought from the area of red Carboniferous beds that are associated with volcanic rocks and veins of quartz in the country between South Attleboro and North Attleboro, Mass., and Diamond Hill, R. I. The mass of quartz at Diamond Hill bears the closest resemblance to these agates, but so far as is now known no agate has been found at Diamond Hill. The pebbles of agate are found on the beaches on Block Island, on the north shore of Marthas Vineyard, and as far east on the Elizabeth Islands as Tarpaulin Cove. The southward fanning of these small erratics is like that of the Cumberland iron ore, but the fan extends farther eastward. Cumberland Iron Mine Hill and Diamond Hill, in Rhode Island, lie respectively 3 and 5 miles east of Woonsocket, and the eastward fanning of the drift tailings is consistent with the positions of the Diamond Hill quartz mass and Iron Mine Hill.

Along with the agate pebbles on the beaches at Naushon, on Marthas Vineyard, and on Block Island there are vein quartz pebbles having the peculiar encrusting growth of quartz that is seen on the pebbles found at Diamond Hill and a few other places within a radius of five or six miles from it. On Block Island there are also pebbles of vein quartz in the drift on beaches where the country rock is a black schist, undoubtedly one of the Carboniferous rocks that crop out in Narragansett Bay. This material confirms the impression made by the agates carrying a reddish shaly trace of the country rock, namely, that the source of all these veinstones lies in exposures of rock swept over by glacial sheets moving southward through the Narragansett Bay region.

CHIASTOLITE SCHIST PEBBLES

Pebbles and glaciated fragments of the well-known chiastolite schist of George Hill, in the town of Lancaster, Mass., are found on Block Island. A fragment of this rock was found on the beach under Mohegan Bluffs about a mile west of Southeast Light in 1915, and pebbles of the same material were found on the east beach south of Clay Head in 1916. The andalusite phyllite of George Hill is known only in boulders, but these boulders may have been derived from rock in place there beneath the glacial drift. The distance from George Hill to the south coast of Block Island is about 91 miles, in a direction 3° east of south.[1]

ABSENCE OF KAMES AND ESKERS

Sections along the shore of Great Salt Pond and elsewhere on the island show stratified beds of gravel, sand, and clay, but wherever the stratigraphic position of these beds has been determined they have proved to be pre-Wisconsin glacial deposits. No stratified Wisconsin glacial deposits that have a distinctive topography are found on the island.

Post-Glacial or Recent Deposits

After the Wisconsin ice sheet disappeared the vegetation of the island, including that in the peat bogs and marshes, began to grow in sheltered positions along the shore of the sea, but no trace of vegetation is found on the surface of the Wisconsin drift of the island above its present swash line. Vegetal deposits were laid down in swamps and peat bogs of fresh-water origin and in marine marshes.

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[1] For references to the andalusite and chiastolite phyllite of Lancaster, consult C. T. Jackson: An account of the chiastolite or nacle of Lancaster: Boston Jour. Nat. Hist., **1**, pp. 35–62, 1837. See also Perry, J. H., and Emerson, B. K., The geology of Worcester, Massachusetts, p. 28, 1903.

FRESH WATER SWAMPS AND PEAT BOGS

Most of the swamps and peat bogs lie on the south side of the island, along the west coast, and along the east coast between Harbor Pond and Sands Pond. They occupy depressions that are presumably of less depth than those which form the site of the numerous so-called ponds or glacial lakelets of the upland parts of the island. All the depressions now occupied by swamps were originally lakelets in which aquatic plants took root. By the addition of other plants, including some trees as soon as the vegetable mat permitted their growth, the depressions were filled to the level at which water will stand in them.

Nearly all the swamps yield peat. No exact estimate of the quantity of this peat has been made, but peat was used as fuel from about 1750 until after 1875, in which year 544 cords were dug on the island. According to Livermore[1] peat has been found on the west coast from highwater mark to a line a quarter of a mile out in the sea.

MARINE MARSHES

The vegetal deposits in tidal water are limited to small patches, most of them along the shore of Great Salt Pond. This body of water appears to have had no direct connection with the sea when the island was settled in 1662. About 1686 an opening was made in the beach on the west side in an attempt to form a harbor, which was made but not long maintained. In 1873 another opening was made, which has been enlarged, and the water of the so-called pond has fallen to sea level, with consequent effects on the growth and the area of the marsh bordering it.

WAVE AND CURRENT ACTION

The striking effect of the action of the sea on the coast of the island is seen in the steady erosion of Mohegan Bluffs, on the south coast, and of the cliffs at Clay Head. Wave cutting has been everywhere somewhat abated by the boulders and smaller erratics that accumulate on the beach. Some of these were derived from the Wisconsin drift that lies on the surface of the island, but many more were derived from the wasting of the bed of Montauk till. At certain points where this bed stands at a high angle in the bluffs the boulders that have accumulated on the beach reveal at once their source.

The large quantity of clay in the Montauk till and in the underlying Gardiners clay causes numerous landslides. Large slices of the bluff slip down. Certain gullies show that rainwater helps to carry the bluffs back above the reach of the waves, which undermine and remove the materials delivered by landslides to the beach. No exact estimate of the rate of recession of Mohegan Bluffs is available, but the Coast Survey chart of the island issued in 1914, which shows the coast line as it existed in 1913, furnishes a basis for concise comparisons in future years.

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[1] Livermore, S. T., A history of Block Island. Hartford, Conn., 1877, p. 29.

Sandy Point, at the north end of the island, is continued under water as a long, narrow spit or bar to the site of an island that was tied to Block Island by a bar that was passable on foot at low tide. According to Livermore, the land at the end of the point, which was called "the Hummock," was a small elevation covered with bushes and small trees, including wild plum trees. It appears to have been washed away about a hundred years ago. Sandy Point now stands at the north ends of two beaches, one crescentic in form, making southeastward past Cow Cove toward Grove Point, and the other forming the straight shore of the west side of Corn Neck. Between these two beaches lies Sachem (Chagum) Pond. The beach on the west side is backed by a line of dunes.

The beach on the west side, at Great Salt Pond, is tied to two small drift islets, which partly inclose that body of water.

Crescent Beach, on the east coast, is the longest stretch of beach on the island that is unbroken by headlands, and is near the center of population during the summer. In the southern part of Corn Neck it is cut back into low bluffs, and farther south it is thrown across what would otherwise be open passageways into Great Salt Pond. The beach is swept by gales that veer from northeast round to southeast and is constantly undergoing minor changes that involve a slow gain of the sea upon the land. It is notable for its fine black sand, most of which accumulated in the form of dunes south of its mid-point. The beach has derived a large share of its material from Clay Head, but some pebbly drift is fed into it from the bluffs south of Clay Head.

Were it not for the southern stretch of this beach the sea would pass freely between the two main parts of the island. At least two or three small islets of glacial drift that lie in or near these cordons of sand are tied by them to the island. (See Plate 31, fig. 2.)

DUNES AND WIND ACTION

Narrow tracts of low dunes that are well tufted with beach grass lie back of the east beach and along the west side of Corn Neck. The sand is composed mainly of quartz, garnet, and black iron ore or magnetite, which are washed by the waves out of the glacial drift. The magnetite sand deserves special mention because of its local abundance.

THE BLACK-IRON SAND OR MAGNETITE

The east shore of Block Island, along the bathing beach, abounds in magnetic iron sand, which is blown up into low dunes, from which, in years past, the market was supplied with blotting sand in the days of quill pens. (Plate **32**, fig. 1.) Many years ago a large horseshoe shaped magnetic separator was devised and installed in a factory on the beach. The remains of this instrument, including the huge magnets, were seen as late as 1916. (See Plate **32**, fig. 2.)

In the early 90's Edison[1] investigated the black sand of Long Island by boring holes along the beach and inland. He found that along the beach in one year there was an aggregate thickness of 12 to 15 inches of black sand for 8 or 10 miles; yet in the next year hardly any could be found. He therefore abandoned the attempt to treat the deposits commercially.

The black magnetic iron sand of Block Island is washed out of the glacial drift along the shore by the sea. The drift on the island carries much waste derived from beds of magnetiferous schist of Carboniferous age in the Narragansett Bay region. These beds are probably the chief source of the magnetite, but minute crystals of magnetite are abundant in many igneous and crystalline rocks of southern New England, and Shaler found that traces of magnetite are very generally distributed in the glacial sand in this region.

GREAT SALT POND

The largest body of enclosed water on the island is Great Salt Pond, which has an area of about 1,000 acres. It occupies a great depression between the northern and southern parts of the island and in places reaches depths of 52 feet below mean sea level. The bottoms of Trims and Harbor ponds, which lie southeast of Great Salt Pond, also lie below sea-level. Great Salt Pond is separated from the sea on the west by a cordon of beach sand, which ties in two small islets of glacial sand. Between these islands a navigable canal has been dredged to a minimum depth of 25 feet. An earlier canal dug north of these islets is now filled with sand. Crescent Beach, on the east side of Great Salt Pond, forms a barrier extending from the Harbor to the southern part of Corn Neck, but it includes islets of glacial material, from which much coarse debris is eroded. Between the beach and Great Salt Pond a small islet, which has cliffs on its west side, supports a small barrier beach that partly separates Trims Pond from Great Salt Pond.

Great Salt Pond, by reason of a channel cut through the western barrier beach, now forms an excellent harbor of refuge for coastwise steamers and is resorted to by naval vessels engaged in manoeuvers in the neighboring sea. Although the northward drift of the sand along the beach threatens to close the canal, its value will justify the occasional expense required to maintain it.[1]

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[1] Edison, Thomas E., Letter to J. B. Woodworth dated Nov. 22, 1893.

At the north end of Great Salt Pond a small island is so tied in by crescentic beaches as to cut off from the main body of water a small lagoon. On its northeast side this lagoon has in turn thrown a crescent barrier beach across a yet smaller indentation of its shore line. Both these barrier beaches were doubtless produced by similar processes, but they came into existence in succession, the earlier having been formed at the original head of Great Salt Pond. Both are examples of what Gulliver has called "bay-bars."[2]

ECONOMIC GEOLOGY

The black-iron sand of the island was gathered and shipped at one time for commercial use, as already noted. The white Cretaceous clay or "kaolinite" at Clay Head is not favorably located for commercial exploitation, and the quantity available is not certainly known.

The water resources of the island are adequate to supply the usual population and passing vessels. Some of the high-lying ponds on the main part of the island furnish supplies of potable water. These ponds appear to lie in hollows over the Montauk till, the clay of which forms an impervious bottom for water derived from the gravel and sand that overlies the boulder clay.

A few wells have been driven on the east side of Block Island to obtain water for the use of the summer hotels. Boulders may be encountered at three horizons. Beneath the upper boulder clay (Montauk) a well should encounter beds of water-bearing gravel (the Herod), which is underlain by beds of sand (Jacob) and fine gravel. These beds occur at all levels from the surface to and below sea level, and as they are in places folded and contorted no rule can be given to determine the depth at which water-bearing gravel or sand may be found at any given place on the island.

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[1] C. T. Jackson's map of Block Island, the result of a reconnaissance survey made in October, 1839, shows an entrance into Great Salt Pond which lay north of the present canal and was known as "Old Breach." See report on the Geology of Rhode Island, 1840.

[2] See Shore-line topography, pp. 201–206.

BIBLIOGRAPHY OF THE GEOLOGY OF BLOCK ISLAND

Block Island was included in an official survey made in 1839 by Dr. C. T. Jackson.[1] Numerous references to the geological features of the island are made in the writings of geologists who have investigated either the Cretaceous clays or the terminal moraine, particularly during the last quarter of the nineteenth century.

A few references to the literature dealing with the island may be found in a report on the geology of Rhode Island published by the Providence Franklin Society in 1887. This work cited no publication earlier than Jackson's report of 1840.

Bibliography of Block Island

1840. Jackson, C. T. Report on the geological and agricultural survey of the State of Rhode Island, 312 pp., map, Providence. Notice by B. Silliman, Jr., in Am. Jour. Sci. and Arts, **40**, pp. 182–194 (1841).

Gives the results of a survey of Block Island made in 1839. Describes the topography and geology. Compares the granite of the boulders to the granite in the region about Kingston and infers that the boulders were derived from that region. Calls the boulders and the soil in which they are embedded "diluvial" and the underlying beds "Tertiary." Finds that this underlying formation consists of alternate beds of clay and white sand. Notes that bog iron is mixed with gravel at the south end of the island and at Clay Head, where the beds are folded and dip to the northwest. Deprecates the former ruinous practice, sanctioned by the town of New Shoreham, of selling cobblestones from the shore for paving the streets of New York and the consequent loss of land on the south coast.

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1887. Providence Franklin Society. Report on the geology of Rhode Island, 130 pp., ills., Providence. Includes a paper by C. T. Jackson entitled "Catalogue of rocks, minerals, and soils collected during the geological survey of Rhode Island in the summer of 1839."

Cites most of the references here given to the bibliography of the geology of Block Island.

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1897. Crosby, W. O. Contribution to the geology of Newport Neck and Conanicut Island: Am. Jour. Sci., 4th ser., **3**, pp. 230–236.

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PART III

GEOLOGY OF CAPE COD AND THE ELIZABETH ISLANDS

CHAPTER I

GEOLOGY OF CAPE COD

By J. B. Woodworth

GEOGRAPHY

Cape Cod proper is a modern sand bank built up at the north end of a remarkable peninsula that extends as a great hook into the sea from the southeast corner of Massachusetts, but the name Cape Cod is commonly applied to the peninsula itself, which may be defined as including the land between Cape Cod Bay and Nantucket Sound and even the land still farther west, between Cape Cod Bay and Buzzards Bay. The precise boundary between Cape Cod and the mainland may be conveniently drawn to follow the Cape Cod Canal and Manomet Creek, but it may be drawn from the head of Buzzards Bay northeastward across the narrow neck of land that separates Buzzards Bay and Cape Cod Bay to a point midway between Sagamore Beach and Peaked Cliff, on the shore of Cape Cod Bay. In the official language of the Commonwealth of Massachusetts Cape Cod is synonymous with Barnstable County. The Elizabeth Islands, which lie farther southwest, form a part of Dukes County.

LOCATION AND AREA

Cape Cod lies between parallels of 41° 30′ and 42° 5′ north latitude, and meridians 69° 55′ and 70° 46′ west longitude. It presents a rectangular outline to the ocean, and its southern coast is fended from the open sea by the islands of Nantucket and Marthas Vineyard. It has a milder climate and on the whole warmer sea water on its southern than on its eastern and northern coasts. The eastern coast, which trends west of north, is exposed to the waves of the Atlantic, the effect of which is moderated by an extensive offshore submarine shoal known as Georges Bank. The southern, broader part of the peninsula, which extends eastward from Buzzards Bay, has not inaptly been called the arm of the Cape. The narrow extension that rises at right angles to this part has been called the forearm of the Cape, and the incurled sand bars at the north end have been called the fingers or hand.

The area of Barnstable County in 1894 was 434 square miles.[1] The area of the coastal lands, particularly those on the forearm of the Cape from Nauset

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[1] Henry Gannett, A Geographic dictionary of Massachusetts, Bull. U. S. Geol. Survey, **116**, p. 10, 1894.

Harbor northward to Highland Light, has been gradually reduced by the inroads of the sea ever since the country was settled, and although small areas of beach flats are built up from time to time between headlands or at the east side of the end of the Cape, the total area of the Cape is reduced a few acres every year.

TOPOGRAPHY

The Cape Cod district is a partly submerged mass of glacial material, which consists of the Plymouth interlobate moraine on the west side of Cape Cod Bay, other interlobate glacial deposits on the east side of the Bay, and a lobate moraine whose frontal outwash plain extends from Chatham to Falmouth and is bordered on the west by the moraine of a glacial lobe that lay west of the Plymouth interlobate axis. Cape Cod Bay lies in the broad, shallow depression that was occupied by the glacial lobe about which the deposits of the Cape are grouped.

The south side of the Cape along the shore of Buzzards and Cape Cod bays is traversed by morainal hills, which in places in and near the town of Sandwich reach a height of 200 feet above sea level. The plains south of this belt of morainal country rise to the same elevation as the hills in Sandwich and decline southward to or nearly to sea level, although they usually confront the Sounds with a low bluff. The inner limit of the plains decreases in height both ways from the axis of the moraine in the northern part of the town of Sandwich, south of the Manomet creek passage.

The arm of the Cape from Nauset harbor northward consists of three well-defined plains, which lie back of the morainal belt. Two of these tracts, the "Nauset" or Eastham plain and the plain in North Truro (see Plate 25, fig. 2), stand between 60 and 70 feet above sea level. Between them lies the deeply creased high plain of Wellfleet and Truro, whose surface attains a height of 150 feet. The tip of the Cape is formed by a large hook of beach sand and dunes, partly enclosing Provincetown harbor. Another large sand bar, or a series of sand bars, lies at the southeastern versant of the Cape. In the coastal lagoons and in the inlets, particularly those bordering Cape Cod Bay, there are large tracts of marshland.

On the side of the Cape facing the ocean there are steep cliffs of gravel and sand, and on the arm of the Cape, in Wellfleet and Truro, on the Bay side, there are lower cliffs. The action of the sea on the side where it has been most effective has given a graceful curve to the coast line.

The Cape Cod peninsula forms the northeastern emerged part of the Atlantic

Coastal Plain, but it is of more recent date than the Coastal Plain south of the glaciated area, and some geologists would not consider it a part of the coastal plain.[1] J. W. Powell,[2] founder of the modern science of physiography in the United States, specifically included in the region within the "Atlantic plain," a region lying east of the Piedmont Plateaus. Keith[3] assigns to the Coastal Plain the Cape Cod peninsula and a "narrow tract along Massachusetts Bay east of a line running through Onset, Kingston, and Scituate."

HYDROGRAPHY

Lakes and Lakelets

The Cape includes many lakes but only a few rivers. The plains of the southern part of the Cape are dotted over with lakes of many sizes, the largest a mile or more in length. The bodies of water that are locally called "ponds," probably because they differ from the lakes, which may be considered expansion of streams, occupy depressions that were left by the melting of masses of former glaciers and may be classified as ice block holes and kettlehole lakelets. A few of the lakelets, such as those in the towns of Mashpee and Falmouth, are sources of streams, partly because ancient channels of outflow have been so adjusted to the water level as to permit this mode of discharge. Other basins form more or less open channels or chains of lake-like stretches of water which open southward to the sea. Bass River, which lies between the towns of Yarmouth and Dennis and forms an inlet into the Cape from the south, approaches within a little less than 3 miles the north shore of the Cape. A small creek at the east side of the entrance of Barnstable Harbor reduces the portage for small boats to about two and a third miles. A similar short portage across the main arm of the Cape was used by Governor William Bradford in the winter of 1627 in going to the aid of an English ship that was wrecked on the bar at Chatham while she was on her way with passengers to Virginia. Bradford appears to have crossed southwest of Orleans to one of the coves at the head of Pleasant Bay.

The inlets and coves about Chatham and Orleans are unfilled depressions in glacial deposits. A small group of lakelets lies east of Wellfleet, and there are others farther north, toward Truro, deep-set in the wooded, high glacial plain.

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[1] See N. M. Fenneman, Physiographic divisions of the United States, Annals Assoc. American Geographers, **6**, p. 45, 1917. Fenneman writes: "If it be assumed that they [the New England Islands] are purely accumulations of glacial drift on the sea bottom they are not technically coastal plain."

[2] J. W. Powell, Physiographic regions of the United States. Nat. Geog. Monographs, **1**, No. 3, May, 1895, pp. 75–76.

[3] Arthur Keith, Topography; in Surface Waters of Massachusetts, by C. H. Pierce and H. J. Dean: Water Supply Paper 415. U. S. Geol. Survey, 1916, p. 18.

Two ponds that lie close together may be separated by a narrow bar or strip of land formed by the waves. These interlake bars are formed by the cutting down of slender ridges of drift or knolls and the filling up of narrow passages between the ridges. A good example of this action may be seen along the railroad between Harwich and Brewster, where a bar separates Long Pond from Bangs Pond. Another such bar lies west of ''Great Hill," near Chatham.

Most of these glacial lakelets have steep banks of gravel or sand. Some of those on the south side of the Cape once had outlets at levels several feet above their present surfaces, and from a few of them, as noted above, the water flows out. Several of these lakelets are more than 50 feet deep.

Mr. William Gould Vinal[1] gives the following figures showing the areas and the maximum depths of several ponds on the Cape:

Name	*Township*	*Estimated area in acres*	*Greatest depth in feet*
Moon[2]	Provincetown	?	3
Long	Wellfleet	34	44
Great	Eastham	112	32
Little Cliff	Orleans	20	54
Cliff	Brewster	141	81
Baker's	Brewster	88	63
Cobb's	Brewster	21	11
Mill	Brewster	110	9
Long	Harwich	778	66
White	Chatham	35	55
Fresh	Dennis	25	9
Scargo Lake	Dennis	60	48
Long	Centreville	69	23
Peter's	Sandwich	176	48
Spectacle	Sandwich	151	39
Mashpee	Mashpee	395	68

HARBORS AND CREEKS

The only large harbor on Cape Cod is at its extreme north end, inside the curved sand spit formed of waste worn from the cliffs and thrown up by the winds and waves on what appears to have been, at least in part, a shoal. Provincetown Harbor, which was known to navigators on this coast before Pilgrims landed here in November, 1620, has ever since remained a convenient port of refuge in storms because of its safe approach from the north and west and its outlying position. A depth of more than 20 fathoms is found off the west side of the Cape as far around as Wood End, close to the shore. Between Long Point and Provincetown the harbor has a depth of 9 fathoms, and surveys made by the Coast and Geodetic Survey[1] show that this depth is maintained by the tides and currents.

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[1] William Gould Vinal, Cape Cod Ponds, Cape Cod Magazine, **3**, Sept. 1917, pp. 9–14. The Cape Cod Publishing Co., Wareham, Mass. This article contains a brief popular account of the formation of swamp vegetation in the shallow ponds.

[2] Moon Pond is in Truro, east of the Province Lands.

There are no inlets on the outside of the Cape north of Nauset Harbor, which is a crooked passage into Town Cove at Orleans and which is subject to the encroachment of a bar that is working southward. (See Plate 1). The bays and inlets near Chatham and north of it may be reached from the sea through a shifting entrance across a bar. No bar of the coast is more subject to changes in the position of beaches and bars than that near Chatham. The inside passage from Chatham northward to Pleasant Bay is shoal and is navigable at low water by boats of small draft only.

On the south side of the Cape there are several small ports, such as those at Hyannis and Woods Hole, which meet local needs. They are all due to irregularities in the deposition of the glacial material either in the plain, as at Hyannis, or in the frontal moraine, as at Woods Hole.

Below Provincetown, on the Bay side of the Cape, there are two harbors, one at Wellfleet and the other at Barnstable. That at Wellfleet is due to a break in the continuity of the high glacial plain about Truro, on the north. There appears to have been an unfilled area in the arm of the Cape between this plain and the frontal moraine on the south, about Orleans. The water in this area is shallow, and extensive shoals southwest of it require boats coming from the north to make a long doubling to the south in order to enter the channel. Barnstable Bay is formed by a barrier beach that lies off an incurved section of the frontal moraine in which a shallow tidal inlet has been formed behind the beach. The bottom of the bay on its south side is shallow and shelves off gently to the 20-fathom line. At low tide the bottom is bared for half a mile or more as a flat of sand and mud and, here and there, areas of washed glacial gravel. Plymouth harbor does not strictly lie within the area of this report, but it is directly connected in origin with the Cape Cod Bay glacial lobe. The depression in the drift which the bay occupies appears to have been formed by a lobelet of ice on the west side of the lobe which was formed by the resistance offered to the ice by Manomet Hill.

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[1] H. L. Marindin, On the changes in the shore lines and anchorage areas of Cape Cod (or Provincetown) Harbor as shown by a comparison of surveys made between 1835, 1867, and 1890, U. S. Coast and Geodetic Survey, Appendix No. 8 to Report for 1891. Part 2, pp. 283–288, with plates Nos. 11, 12. See also Henry L. Whiting's report in Appendix No. 12 to the Report of the Coast Survey for 1867.

CARTOGRAPHY

Before Henri de Champlain and Captain John Smith made the voyages to New England, Cape Cod was shown very inaccurately on maps of the north Atlantic coast. A critical essay on early maps of the coast line, with illustrative charts, is given by Justin Winsor.[1] Maps sufficiently accurate to be useful for comparing the coast line at different dates began to appear with the growing need for them in naval operations at the time of the Revolutionary War. The most reliable of these maps is one of the New England coast prepared from surveys made in 1777 and published in 1780 by Joseph Friederich Walsh Des Barres. Professor Henry Mitchell mentions a corrected edition of this chart by Matthew Clark. James D. Graham made accurate surveys of Cape Cod and Provincetown harbor for the United States Government in 1833–35, before surveys were made by the United States Coast Survey. Preliminary coast charts were first issued by the Coast Survey in 1857. Their scale was 1/200,000 for Cape Cod and 1/50,000 for Provincetown Harbor. Other harbor charts were issued for Barnstable in 1861, Wellfleet in 1853, Bass River in 1857, and Hyannis in 1850. More recent surveys and editions of coast charts are listed in the catalogue of publications issued from time to time by the Coast and Geodetic Survey.

Special charts and land maps were prepared in connection with the work in Cape Cod Canal. A history of the discussion and development of this project, which dates from 1676, is given in an account published by the Massachusetts commissioners in 1862.[2]

The topographic maps of the United States Geological Survey, which were made from surveys completed in 1886, were preceded by two maps of the State of Massachusetts that included Cape Cod peninsula. The first of the state surveys was ordered by the legislature in 1830 and made under the direction of Simeon Borden. The manuscript map was completed in 1840 and published in 1842.[1] This map was revised in 1860 by H. F. Walling[2] under authority of the legislature. The map of Cap Cod published in 1871 is based on surveys of Barnstable County made by Walling in 1858, but includes corrections of the coast line supplied by the Coast Survey chart of 1857.

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[1] Justin Winsor (editor), Narrative and critical history of America, Boston, 1884. For early maps of New England, see vol. 3, pp. 381–384. The cartography of the northeast coast of America from 1535 to 1600, 4, pp. 81–102. See also Maps of the eastern coast of North America, by B. F. DeCosta, 4, pp. 33–80 and General atlases and charts published in the Sixteenth and Seventeenth centuries, pp. 368–394.

[2] Report of the Joint Committee of 1860 upon the proposed Canal to unite Barnstable and Buzzards bays, Public Document No. 4, Boston, State Printers, 1864, pp. 165. Maps and plates. Appendix I, pp. 58–76, gives a list of shipwrecks around Cape Cod from 1843 to 1859.

DESCRIPTIVE GEOLOGY

(See Plates 1 and 2)

Earlier Reports

Captain John Smith made perhaps the first report on the geology of southeastern New England, including Cape Cod, in these words: "From 43. to 41. and a half, an excellent mixed coast of stone, sand and clay[3] . . . " No more complete account of the geology of Cape Cod was published until the report of President Edward Hitchcock, undertaken for the Commonwealth, appeared in the publications of the State survey.[4] One result of these official surveys was a geological map of the State, which, in the issue of 1841, represented Cape Cod as "diluvium," a term having the same meaning as Pleistocene in modern geological literature when limited to the glacial deposits. The final report appeared after the publication, in the same year, of Louis Agassiz's famous "Études sur les Glaciers," which led Hitchcock to suggest, in a postscript of his report, the possibility of glacial action on Cape Cod. Hitchcock had already, in the body of his report, so he states, called in the aid of ice to explain the mounds of gravel and sand. In the application of the glacial theory of Agassiz to the Cape Cod district the question arose whether "the whole of Cape Cod is nothing but a vast terminal moraine, produced by a glacier advancing through Massachusetts Bay, and scooping out the materials that now form the Cape." He then goes on to state that the moraines at Plymouth and Truro would form a part of the lateral moraine, and that probably most of Nantucket and Marthas Vineyard might be regarded as moraines of the same glacier when it extended farther south.[5]

He considered the laminated clays on the Cape a strong obstacle to this hypothesis, as indeed they were if the theory of a single advance of the ice sheet into the district were held. The constructive geological work on Cape Cod from the time of Edward Hitchcock's conception of the modeling of the features of the region by glaciation has verified his grasp of the subject, the chief gain consisting in the recognition of a succession of ice advances, between which clay and other deposits that are not strictly glacial have been laid down.

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[1] Published by Morse and Breese. Engraved on copper by George G. Smith. Boston, 1842.

[2] H. F. Walling and O. W. Gray, Official topographical atlas of Massachusetts, 1871; Plates 70-71, Barnstable County, with insets of Dukes and Nantucket counties. Scale 2½ miles to an inch.

[3] Captain John Smith, New Englands Trials, London, 1622, 2d ed. Reprinted in Everyman's Library, Chronicles of the Pilgrim Fathers (1910), p. 245.

[4] Edward Hitchcock, Report on the geology, mineralogy, botany, and zoölogy of Massachusetts, Amherst, 1833, 2d. ed., 1835. Report on a re-examination of the economical geology of Massachusetts, Boston, 1838, 139 pages, House Doc. No. 52. Final Report on the geology of Massachusetts, Amherst, Northampton, 1841, 4 to 831 pages.

[5] Edward Hitchcock, Final report on the geology of Massachusetts 1841, p. 9a, postscript.

In 1856[1] Hitchcock referred the high terraces of Truro to his group of "moraine terraces," which he regarded as having been heaped up and scooped out by a glacier.

In 1871, Charles H. Hitchcock compiled the data for a revised geological map of Massachusetts, on which Cape Cod, although properly described in the accompanying text as wholly composed of drift, was through some error in printing, colored and indicated in the legend as Miocene Tertiary.[2]

In 1878 Mr. Warren Upham[3] published the results of a rapid reconnaissance of the glacial deposits of Cape Cod and the neighboring islands, confirming the view of Clarence King[4] that the terminal moraine of an ice sheet lay in this region.

In 1881 Shaler,[5] writing when the glacial drift was still thought to have been deposited during a single ice invasion, estimated the amount of material in the terminal moraine on the islands and in the drift on Cape Cod.

The correlation and explanation of the moraines of Cape Cod and the neighboring islands on the south was finally made in the masterful generalization of the superficial glacial deposits of the northern states by T. C. Chamberlin[6] in 1883. In this paper the author developed the theory of glacial lobes with lobate and interlobate frontal moraines, which completed the explanation suggested by Edward Hitchcock as early as 1841 for the thick deposit of drift that extends northward from the lobate moraines on the south side of Cape Cod into the region about Manomet Hill and the Plymouth woods. This deposit was laid down between an ice lobe west of the Cape Cod region and one in Cape Cod Bay, and a similar deposit formed the forearm of the Cape north of Nauset inlet.

[1] Edward Hitchcock, Illustrations of surface geology, Smithsonian Contributions to Knowledge, Washington, April, 1857, p. 33.

[2] H. F. Walling and O. W. Gray, Official topographic atlas of Massachusetts, Boston, 1871. Map on pages 18–19, see note on p. 22.

[3] Warren Upham, in C. H. Hitchcock, Geology of New Hampshire, Concord, 1878, **3**, pt. 3, pp. 300–303.

[4] Clarence King, See G. F. Wright, Proc. Boston Soc. Nat. Hist., **19**, 1876, pp. 60–63.

[5] N. S. Shaler, in Shaler and Davis, W. M., Illustrations of the Earth's Surface, Glaciers. Boston, 1881, pp. 57–58.

[6] Preliminary paper on the terminal moraine of the second glacial epoch, Third Ann. Rept. of the Director, U. S. Geol. Sur., 1881-82, Washington, 1883, pp. 291–402.

The geologic mapping of the Cape Cod peninsula in detail was not undertaken until 1889, when Mr. C. W. Coman prepared maps showing the distribution of the unstratified drift or till on the surface, the distribution of the superficial stratified gravel and sand, and the changes in the swamps and marshes, as well as the narrow areas of beach and dune sand along the coast. This work was done under the direction of Shaler for the United States Geological Survey.

In 1897 Grabau[1] described the plains of Truro, Wellfleet, and Eastham on Cape Cod. The northern of these three plains, the Truro plain, which has an average elevation of 80 feet, he ascribed to deposition in front of the ice in the form of a delta, but was doubtful whether it had ice-contact slopes on the east, north, and west. The Wellfleet plain, which has an average elevation of 140 feet, he regarded as presenting a doubtful ice-contact slope in the depression between the Truro and the Wellfleet plain. The Eastham plain he noted as sloping westward from the present eastern coast, where the surface has an elevation of 75 feet, and as showing construction by streams flowing from the east, off the present coast of Cape Cod. He regarded the Truro plain as a product of streams flowing from the northeast and northwest at a time later than the formation of the highest Wellfleet plain. He favored the hypothesis that glacial barriers held up the water in an embayment of the ice front rather than the hypothesis of marine submergence. Grabau was the first geologist to show that the arm of the Cape, which occupies the position of an interlobate moraine, presented evidence that a glacial lobe once lay outside of Cape Cod and that the deposits were mainly waterlaid instead of normal lateral accumulations of till.

In 1898 Shaler[2] published a report on the geology of Cape Cod in which he recognized a series of deposits of gravel, sand, and clay beneath the surface moraine, and hence older than it. Among these deposits he placed the dark clay (here tentatively correlated with the Gardiners clay) which he included in his ''Barnstable series.'' He described other divisions (the ''Truro series'' and the ''Nashaquitsa series''), but as later work has shown that these divisions include the clay of the ''Barnstable series'' as well as other beds, the nomenclature of Shaler's report has been replaced by tentative correlations with the deposits of Long Island and Marthas Vineyard. There is doubt as to the true position of the beds of clay at Barnstable, and although the name ''Barnstable clay'' might be useful for local designation, and although Shaler's use of ''Barnstable series'' has priority over the name Gardiners clay, used by M. L. Fuller in 1905, it is not certain that the clay bed at Barnstable lies at the same horizon as the Gardiners clay, or which of the other clay beds of the district can be correlated with the clay bed at Barnstable.

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[1] Amadeus W. Grabau, Science, new series, 5, 1897, pp. 334–335.

[2] N. S. Shaler, Geology of the Cape Cod district, Eighteenth Annual Rept., U. S. Geol. Survey for 1896–97. Part II. Washington, 1898, pp. 497–593.

In 1906 M. Maurice Allorge,[1] then a student working under William Morris Davis, visited the Cape, and wrote a sketch of its geography, which included a brief account of the moraines.

In the same year J. Howard Wilson,[2] in a thesis prepared for a doctorate, described in considerable detail the glacial deposits of Cape Cod and presented an argument for the former existence in Cape Cod Bay of a glacially barred lake, which he named "Lake Shaler." In the same paper he advocated the hypothesis that the glacial drift on Cape Cod and Nantucket had been brought to the district by a glacier that moved southwestward along the front of the main ice sheet on the continent from a source in Newfoundland, a view that has not received acceptance. In 1914 Fuller, in attempting to correlate the Pleistocene deposits north and east of Long Island with the formations worked out on that island, referred the bed of dark clay on Cape Cod to the same horizon as the Gardiners clay — a horizon in the older Pleistocene. He thought that the sandy upper part of the bed on the Cape represented, as an inseparable member, the Jacob sand of the islands on the southwest. He referred to the younger Herod gravel several deposits of gravel and sand in the coastal bluffs of the Cape. The banded pebbly clay till in these bluffs, as he thought, represents the Montauk till, and the beds of gravel overlying this till he regarded as of the age of the Hempstead gravel. Fuller's[3] paper was the first one to attempt to correlate the various glacial deposits throughout the New England Islands, Cape Cod, and adjacent parts of the mainland about Boston and even farther north.

It is now believed that, so far as known, the entire district that lies above sea level is composed of Pleistocene glacial or closely allied formations nearly identical with those on the islands to the south.

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[1] Maurice Allorge, Esquisse geographique du Cap Cod, Annales de Geographie, No. 84. xv^{e} Année 15 Nov., 1906, pp. 443–448; pl. xxii.

[2] J. Howard Wilson, The glacial history of Nantucket and Cape Cod, with an argument for a fourth centre of glacial dispersion in North America. New York, The Columbia University Press, 1906. See pp. 4–50 on upper Cape Cod; ch. VIII, at pp. 52–66, on Lake Shaler, a glacial lake in the Cape Cod region; ch. IV, at pp. 67–89, on An argument for a fourth centre of glacial dispersion in North America.

[3] M. L. Fuller, The geology of Long Island, Prof. Paper 82, U. S. Geological Survey, see pp. 219–222, and table at p. 220.

The Bed Rock Basement

The bed rock of the mainland of southeastern Massachusetts passes below present sea level along a curved line drawn from Brant Rock, on the open coast, in the town of Marshfield, southward through Plymouth to the head of Buzzards Bay and thence southwestward on the south side of the ledges skirting the coast of the Bay about New Bedford. There are two means of determining the depth of the bed rock basement beneath Cape Cod. One, the direct method, depends on deep borings; the other depends on projecting the slope of the surface of the bed rock on the mainland beneath Cape Cod. The first method, by reason of the lack of more than one boring on which to rely for evidence, offers little more than a check on the other.

In 1905 the water commissioners of Provincetown caused to be put down in the dunes near the eastern limit of the town on ground then occupied by the pumping station, a driven well which, according to the report of the commission, reached a depth of 420 feet. According to Mr. J. Henry Blake, of Cambridge, Mass., who visited the site in June and August, 1905, the well was put down to the depth of 450 feet from the surface, where the drill encountered a rock, a fragment of which Mr. Blake collected at the time. This specimen, which is 19 mm. long, is a fresh looking grayish-green coarsely crystalline hornblende syenite, unlike any syenite exposed between Newport, R. I., and Portland, Maine. Near Portland, however, as I am informed by Professor John E. Wolff, a piece of drift rock of the same facies was found some years ago by Dr. George P. Merrill and is now in the collections of the petrographical department of Harvard University.

It was the opinion of the well borers, so far as could be learned by inquiries made at Provincetown in 1915, that the rock was a boulder, because the well borers stated that it moved when struck by the drill. Thus the only well that has been put down on Cape Cod to a depth near the presumed position of the bed rock floor afforded no decisive information as to the character or depth of the rock. The depth of the floor can be inferred only from borings made at widely separated points on the Cape, and the experience in boring deep wells for potable water does not afford promise that such evidence can be had.

Any attempt to determine the depth of the bed rock floor by projecting seaward the slopes of the neighboring land surface back of Cohasset and Plymouth is beset with doubts and difficulties as to the surface that represents that floor. The eastern coast of Massachusetts, from Cohasset northward at least, appears to end abruptly in a platform that stands from 200 to 300 feet above sea level, confronting from 30 to 50 miles eastward the floor of the Bay of Maine, which lies about 600 feet below sea level, a difference of level of nearly 900 feet in the latitude of Cape Ann, brought about by diastrophic movement. To what extent this drop from the edge of the lowland affects the depth of the bed rock floor under Cape Cod there is no positive evidence.

PRE-PLEISTOCENE FORMATIONS

No pre-Pleistocene formations have been recognized in outcrops on Cape Cod. Beds of upper Cretaceous clay are exposed on the south shore of Nonamesset Island, near Woods Hole, at the southwest corner of the Cape, and Cretaceous beds probably lie not far beneath the surface in the neighboring region, in the town of Falmouth. No deep borings have been made on the Cape to show whether or not Cretaceous rocks lie upon the bed rock floor.

Fragments of Eocene friable shelly marl have been found by W. O. Crosby in the gravel near the top of the bluff south of Highland Light. These drifted fragments appear to have been brought from the north and east by glacial action at the time the Jameco gravel was laid down and are the only known Eocene marine sediments found in the region. They were probably brought from the bottom of the Bay of Maine.

All the beds of gravel and boulders carry fragments derived from the Paleozoic and older rocks of the coastal region of eastern New England. Among these fragments are pebbles of Upper Cambrian quartzite carrying casts of shells of brachiopods. One fragment of semi-quartzite found in 1915 in the gravel bed beneath the "clay-pounds" or supposed Gardiners clay at Highland Light carried Devonian fossils. Fossiliferous Devonian rock has since been found in place in the town of Rowley, Mass.

Drift derived from conglomerate like that of the Carboniferous areas around Boston and in the Narragansett Basin, found in the glacial deposits of the arm of Cape Cod, show that such rocks may form a part of the floor of the Bay of Maine and the outer part of Massachusetts Bay, if not also the floor of Cape Cod Bay.

PLEISTOCENE FORMATIONS

The Pleistocene formations of the Cape Cod district include series comparable to those that form the middle and upper part of the series exposed on Marthas Vineyard and Nantucket. Beds of fossiliferous sand at the lower part of the known section in the Sankaty sand of Nantucket are here placed in the Pleistocene. The formations recognized in the Cape Cod district are shown below in descending order.

Wisconsin glacial deposits:
  Falmouth substage: Falmouth moraine and associated outwash plain.
  Nantucket substage: Deposits of gravel and till and kames; ice-block holes on south side of Cape Cod.
Vineyard interglacial stage: Represented by erosion phenomena.
Manhasset formation:
  Hempstead gravel member (?): Beds of sand about Pleasant Bay and Chatham, which rest on dark clay that may represent Montauk till; also beds of gravel overlying boulder clay (Montauk?) in Barnstable and areas farther east.
  Montauk till member (?): Boulder clay near and east of West Barnstable; deposits forming Great Hill; and pebbly till at Nauset head.
  Herod gravel member (?): Beds of gravel and sand that lie beneath morainal outwash deposits near Chatham; gravel overlying boulder clay in Barnstable.
Jacob (?) sand: Fine yellowish sand 40 feet thick, above blue clay (Gardiners?) at Highland Light; fine yellowish sand about a mile east of Truro station, resting on brownish clay (Gardiners?); sandy beds above clays at West Barnstable; sandy beds overlying blue clay (Gardiners?) near Chatham.
Gardiners (?) clay: Beds of marine clay, at Highland Light, in Truro; similar beds along the shore of Pleasant Bay at West Barnstable; about 1 mile east of Truro station; and about Chatham.
Jameco (?) gravel: Coarse glacial gravel at Highland Light and in bluffs south of it, lying beneath blue clay (Gardiners?).
Sankaty sand: Fossiliferous marine sand in Provincetown well and in well at Orleans.

These deposits will now be described in detail and the evidence for their correlation will be presented. In this account it is convenient to begin with the lowest deposits — the oldest.

PRE-WISCONSIN DEPOSITS

SANKATY SAND

Deposits that are believed to be an extension northward along the coast of the fossiliferous marine sand found in the cliffs at Sankaty Head, on the east coast of Nantucket, were encountered in a well drilled in 1905 on the site of the old pumping works of the city water board at the eastern limit of Provincetown. This well reached a depth of 420 or 450 feet, where the drill struck a rock (syenite) that the drillers believed to be a boulder. Samples of this rock were obtained by Mr. J. H. Blake when the well was drilled, and are now in the geological laboratory at Harvard University. Several samples obtained from shallow wells in the same vicinity consisted of waterworn small glacial pebbles and broken shells.

Mr. Blake's notes and the samples he obtained afford the following data:

A sample taken about 200 feet down consisted of broken shells, in fragments from 10 to 12 mm. long, stained yellow to brownish with iron oxide; apparently existing species of molluscs; also small pebbles and fragments of rock, among which are recognizable a red shale, blue slate, granitic quartz grains, quartz porphyry, whitish quartzite, and a much decomposed ferruginous rock. The rock is typically rearranged glacial gravel like that found at several horizons in the Pleistocene series.

Dr. Dall, to whom the fragments of shells were submitted in 1915, identified them as follows:

Balanus sp.
Lunatia, probably *L. heros* Say.
Venus, doubtless *V. mercenaria* L.
Macoma, probably *M. balthica* L.
Spicula solida or *similis*, of the present fauna.
Echinarachnis sp.

These identifications are only tentative. According to Dall the horizon is probably that of the upper bed at Sankaty Head, Nantucket.

A gray sandy clay containing small grains of yellowish quartz, scales of muscovite, and minute particles of a black mineral, probably magnetite, was encountered at a depth of 300 feet. The clay is free from compound undecomposed minerals, such as the feldspar found in the New England glacial drift deposits, but is apparently an intercalated member of the shell-bearing series of coarse sand and fine gravel.

Mr. Blake collected from material brought from the depth of about 360 feet waterworn yellowish fragments of a sand dollar (*Echinarachnis* sp.).

This scant record of the well at Provincetown seems to indicate that the Sankaty sand there is at least 160 feet thick and that it lies 200 to 360 feet below the surface. It has been reported that *Arca transversa* was found in an artesian well drilled many years ago at Provincetown to a depth of 120 to 200 feet below the surface.[1] This well was drilled near the shore of the harbor at or near the long wharf. *Arca* (*Scapharca*) *transversa* is still living in the sea about Marthas Vineyard, Nantucket, Chatham, and Wellfleet. Its reported occurrence at a depth of 120 feet in this artesian well — a depth about 80 feet nearer the surface than the depth at which the shells reported from a well drilled in 1905 — is doubtful in view of the uncertainty concerning the dip of the Sankaty sand beneath Provincetown.

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[1] W. G. Binney (editor) and Augustus A. Gould, Report on the Invertebrata of Massachusetts, Boston, 1870, p. 149.

Mr. M. C. Atwood, Deputy Collector of Revenue at Provincetown, informed me in April, 1916, that a well was drilled at the end of Central wharf to a depth of 400 feet many years ago. The material passed through was a light gray clay. No good water was found.[1]

Mr. Elmer C. Smith told me in 1916 at Rock Harbor that in about 1890 a well was sunk on his father's land in East Orleans, near the point where the road branches off to go to Pochet Neck. No water was found at a depth of 70 feet, but farther down the drill passed through from 2 to 3 feet of blue clay at a depth of 84 feet and then entered a bed of shells in "beach gravel." The well was drilled at a point about 50 feet above sea level. This shell bed is probably brought up by an anticlinal fold in the Sankaty sand. The washing away of the banks about the crooked inlets between Nauset Harbor and Namequot Point may expose this shell bed above sea level.

The Sankaty sand occurs in Sankaty Head bluff and probably reappears above sea level in the eastern part of Orleans. Its discovery in the wells at Provincetown between 200 and 360 feet below the surface indicates that it underlies the arm of Cape Cod and that it is distributed along the coast of eastern Massachusetts. Beds containing its fauna have not been found on Marthas Vineyard, where, however, there are beds of Pliocene sand containing *Macoma lyelli*, a species not found living elsewhere and particularly abundant in the underlying Miocene greensand.

In his correlation table of Pleistocene formations about the coast and islands of southeastern New England, Fuller[2] placed the fossiliferous beds at Sankaty Head at the horizon of the Jacob sand, a formation that lies upon the Gardiners clay and under the Herod glacial gravel, but the position of what appears to be the Gardiners clay and Jacob sand in the bluff at Highland Light, a few miles southeast of the Provincetown well, suggests that the Sankaty sand lies below the section at Highland Light and that the Jameco gravel is the visible base of that section. The Sankaty sand, with its marine fossils, probably lies at the horizon of the Weyquosque glacial sand and small gravel — that is, it lies very near the base of the Pleistocene series. Its assignment to this horizon agrees closely with Dall's opinion that it represents the upper Pliocene; but just as the Weyquosque glacial sand and gravel at Clay Head on Block Island and at Gay Head and in Nashaquitsa cliffs on Marthas Vineyard are underlain by beds of boulders or by pebbles containing granitic material, so at Sankaty head the beds are underlain by a glacial gravel. Finally, if the rock at the bottom of the Provincetown well is really a boulder it indicates that glacial erratics lie beneath the Sankaty sand. If this view should be supported by further evidence, it would place this marine invasion in an interglacial stage following what was probably the first ice invasion of southern New England. The shell beds carrying *Macoma incongrua* appear to lie below the blue clay at Highland Light, which is of supposed Gardiners age, for a pebble containing that species was found in the underlying gravel, of supposed Jameco age, in the bluff south of the light-house.

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[1] Charles W. Johnson, Fauna of New England, list of the Mollusca: Occasional Papers of the Boston Society of Natural History, **8**, No. 13, Boston, 1915, p. 19.

[2] Prof. Paper 82, U. S. Geological Survey, Washington, 1914, p. 220.

The Sankaty sand may extend northward into Massachusetts Bay and Boston Harbor, and may have furnished the fossil shells and pebbles of agglutinated sand carrying shells such as are found in the drumlins in that region. The deposits supplying these shells there apparently lie beneath the glacial blue clay found in the valleys of the Mystic and Charles rivers. The Dana brothers[1] noted, as early as 1818, fragments of *Mya arenaria* found 40 feet below the surface at Jamaica Plain, and the fragment of a clam shell found at the depth of 107 feet in digging the well at Fort Strong, an earthwork built at the end of August, 1814, in East Boston, at the south end of Noddle's Island.[2]

JAMECO (?) GRAVEL

The end of Cape Cod peninsula from near Wellfleet to Pilgrim Heights, which overlooks the expanded sand hook on which Provincetown stands, includes the two plains described by Grabau as the Truro plain and the Wellfleet plain. For several miles along the ocean side of this part of the Cape there is a bluff whose structure is well exposed at Highland Light and at other points where the sea is undermining it and removing the talus of gravel and sand. Distinct stratigraphic members in this section can be recognized only at Highland Light, where, beneath the surface rubble and wind-blown sand, about 40 feet of fine yellowish sand resembling the unfossiliferous Jacob sand overlies about 40 feet of dark clay containing no stones. This clay has the appearance and stratigraphic associations of the Gardiners clay. It rests on a coarse glacial gravel, which Fuller regarded as the Jameco gravel, and it is overlain by fine yellowish sand that resembles the Jacob sand. Under the lighthouse at the ''clay pounds'' a bed of this gravel about 20 feet thick was exposed in 1915–16 above the beach. Its components are subangular and waterworn pebbles or cobbles, the largest 8 inches in diameter, indicating very strong stream work. Ten feet below the contact of this bed with the overlying clay there is dark-purplish felsite, felsite breccia, and felsite having flow structure, some of it in angular blocks about a foot long. There are also pebbles of gray quartzite, fine red shale, compact argillite, schist, lustrous crumpled phyllite like that at Savin Rock south of New Haven; granitite, gabbroid, and dioritic rock resembling that on the east coast near Boston; and waterworn pebbles of a red conglomerate that resembles some forms of the Roxbury conglomerate found near Boston. In the bluffs north of the clay pounds or near this horizon there were seen also angular boulders (one of felsite) nearly 3 feet long. South of the clay pounds the section changes as it rises on a gentle northward dip to a series of alternating beds of gravel and sand. Farther south it is difficult to trace bed to bed because of the talus.

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[1] J. Freeman Dana and Samuel L. Dana, Outline of the mineralogy and geology of Boston and its vicinity, with a geological map, Boston, 1818, p. 96. The drifted shells are described by W. O. Crosby and H. O. Bullard: Distribution and probable age of the fossil shells in the drumlins of the Boston Basin. Am. Jour. Sci., **48**, 1894, pp. 486–496. Includes a list of 55 species of marine animals collected by Messrs. Stimpson, R. E. Dodge, W. W. Dodge, Warren Upham, W. W. Herman, and others.

[2] Justin Winsor, Memorial history of Boston, **3**, pp. 309–310, Boston, 1881.

Among the coarse fragments found in the gravel about 10 feet below the base of the clay was a quadrangular piece of Devonian fossiliferous semi-quartzite about 6½ inches long, filled with fossil casts. Dr. Ulrich, who examined these casts, stated that the fossils consist of brachiopods, pelecypods, and trilobites, all poorly preserved. He furnished the following list:

Dalmanella sp. Cf. *D. planoconvexa*
Schizophoria sp.
Modiomorpha sp.
Homolonotus; fragments of a trilobite suggesting this genus.

The horizon at which this fragment was found is regarded by Ulrich as Lower Devonian. The rock is made up of fine grains of light blue quartz, which weathers yellowish. At nearly the same horizon in the gravel but farther south and higher up in the cliff on account of the rise of the beds in a fold, a slabby fragment containing small patches of clay was found. These patches look like fossil shells.

In the same beds, near the top of the cliff, at the southern limit of the government lot, I found a flattish finely stratified greenish-hued quartzite showing faint ripple marks and carrying on the flat side three impressions having a hyolithoid outline. One of these impressions was distinctly marked with transverse lines of growth. Dr. Walcott identified this material as a species of *Hyolithes*, probably but not certainly Cambrian.

In a thin patch of lag gravel on top of a bed of fine sand (Jacob?) just north of the Weather Bureau Station, I found a weathered specimen of quartzite showing the parallel closely set ribs of *Scolithus*, a form found from the Lower

Cambrian upward. A large specimen of this scolithoid sandstone or quartzite was found several years ago on the beach at Marshfield, on the opposite side of Cape Cod Bay.[1]

The fossilferous Cambrian pebbles that are scattered widely on the south coast in the glacial drift or in the rearranged drift of the modern sea beaches have doubtless been dragged out of the coarse conglomerate of the Carboniferous rocks of southern Massachusetts and Rhode Island. The pebbles in this conglomerate are not only more numerous but larger toward the southern side of the field. No such pebbles have been found in the conglomerate along the northern border of the district, in the area about Norfolk, or in the area of Roxbury conglomerate near Boston. These Cambrian pebbles were evidently carried southward beyond the present coast in Carboniferous time, from a land where quartzite crops out. The Cambrian pebbles on Nantucket and on the outer part of Cape Cod were therefore probably brought by one or more ice sheets from beds of Carboniferous conglomerate that lay under Massachusetts Bay or on the floor of the Bay of Maine. The conglomerate doubtless derived them from the lost land on the south, southeast, or southwest, which was reduced to a peneplain in middle Mesozoic time and covered in Upper Cretaceous time with sediment that still remains off the south coast in the New England Islands.

At least three erratic fossiliferous Devonian pebbles have been found in southeastern Massachusetts. The first one I found in the moraine on Marthas Vineyard as long ago as 1888. A slabby greenish-gray quartzite or semi-quartzite found in the middle of the island just west of the village of West Tisbury, near a pond on the Tiasquam River, was submitted to Prof. Henry Shaler Williams, who reported on the material as follows:[2]

> Examination of the fossils shows two species, one an *Orthis*, which presents close resemblance to *O. multistriata*, and a fragment of what I take to be a *Spirifera*. It is less than half of a dorsal valve, but what there is of it closely resembles that part of a form which occurs in the Maine so-called Devonian faunas and which is generally called *Sp. cyclopteris*, but is shorter than that species generally is in New York. I am inclined to think it is a representative of the fauna found in the Gaspé sandstone. Correlated with Schoharie and Esopus of New York. Similar rock with this fauna occurs in the northwestern part of Maine about Moosehead Lake, and probably deposited farther south, though I know of no region for it.

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[1] U. S. Geol. Survey Mon. 33, pp. 110, 112, 1899. On the distribution of fossiliferous Cambrian pebbles in the Carboniferous conglomerates of the Narragansett area and on the beaches and in the glacial drift south of this coal field, see also W. B. Rogers, Proc. Boston Soc. Nat. Hist., **7**, 1861, pp. 389–391; W. O. Crosby and G. H. Barton, Am. Jour. Sci. 3d ser., **20**, 1880, pp. 416–420; C. D. Walcott, Am. Jour. Sci. 4th ser., 1898, pp. 327–328. Crosby and Barton noted the occurrence of *Scolithus* pebbles in the Carboniferous conglomerates near Newport, R. I., such pebbles are not uncommon on the beaches of Vineyard Sound.

[2] Letter to Director C. D. Walcott dated New Haven, Conn., April 10, 1889.

For a time it seemed that this Devonian erratic must have been brought by an ice sheet from Maine or from an area north of Boston to Marthas Vineyard; but the pebble lay in the field of the lobate moraine west of the Plymouth interlobate axis and was associated with striae of a glacier that swept down from central New Hampshire across the interior of the Boston and the Narragansett areas and lay quite out of the field of action of the glaciers that ran southeastward across Maine. Shortly before his death Prof. A. C. Packard showed me a quartzitic pebble from the Carboniferous conglomerate east of Providence, in the Taunton syncline, containing a species of *Spirifera* closely resembling the form described by Williams. The Devonian pebbles of southeastern Massachusetts therefore evidently also came into the Pleistocene drift from Carboniferous conglomerate. The Devonian and Cambrian pebbles in the supposed Jameco gravel under Highland Light on Cape Cod and any that may be found in the higher drift beds of the region can therefore hardly be used as a basis of definite conclusions as to the direction of motion of the Pleistocene ice sheets. These pebbles appear to have been shifted northward in Pennsylvanian or Permian time into the gravel beds at a time of local mountain glaciation,[1] and to have been carried southward during the Pleistocene epoch. Upper Cambrian pebbles could not have been brought to southeastern Newfoundland during Pleistocene time because an ice sheet coming from that small gathering ground to Nantucket and Cape Cod would have to maintain its position and course directly along the front of a great regional glacier that was pushing down over New Brunswick, Maine, and eastern New Hampshire, on the edge of the continental platform, in a position that seems physically impossible. The fact that no ice mass radiated out far to the southwest and west is shown by the absence of glacial deposits from the Magdalen islands, in the St. Lawrence Gulf, except some deeply weathered early Pleistocene till discovered by Goldthwaite[2] in 1913. The position of Upper Cambrian fossiliferous sandstone containing *Obolus* on the Avalon peninsula, in southeastern Newfoundland, is quite consonant with the probable extension of a band of these rocks southwestward off Nova Scotia and the present southern coast of New England in late Paleozoic time.[3]

GARDINERS (?) CLAY

Beds of dark clay may be seen along the shore of Cape Cod above sea level at several places, as at Sandwich and thence eastward to West Barnstable;

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[1] Robert W. Sayles, The Squantum tillite, Bull. Mus. Comp. Zoöl. Harvard College, **56**, 1914, pp. 141–175; 12 pls., including map of country south of Boston showing localities.

[2] James Walter Goldthwaite, The occurrence of glacial drift on the Magdalen Islands, Museum Bull. Canada Geol. Survey, No. 14, geol. ser. No. 25, May 12, 1915, p. 11, with maps and illustrations.

[3] See C. D. Walcott's chart showing the distribution of Cambrian formations in the twelfth Annual Report of the Director, U. S. Geol. Survey, for 1890–91, pt. I, pl. XLII, p. 532.

about Chatham and Pleasant Bay; on the Bay side of Truro; and in the so-called "clay-pounds" at Highland Light. The base of these beds is nowhere exposed to view except at Highland Light. Shaler called them the "Barnstable series," a term that was apparently intended to include also certain gravelly clay. Whether the beds of clay on Cape Cod are all of the same age is still uncertain. The only well exposed section that strongly resembles the typical Gardiners section is that at Highland Light, where the dark clay occurs in the form of a large lens that crops out on the coast above the gravel that Fuller called Jameco and below beds of sand that represent either the Jacob sand or a younger deposit. (See Plate **33**).

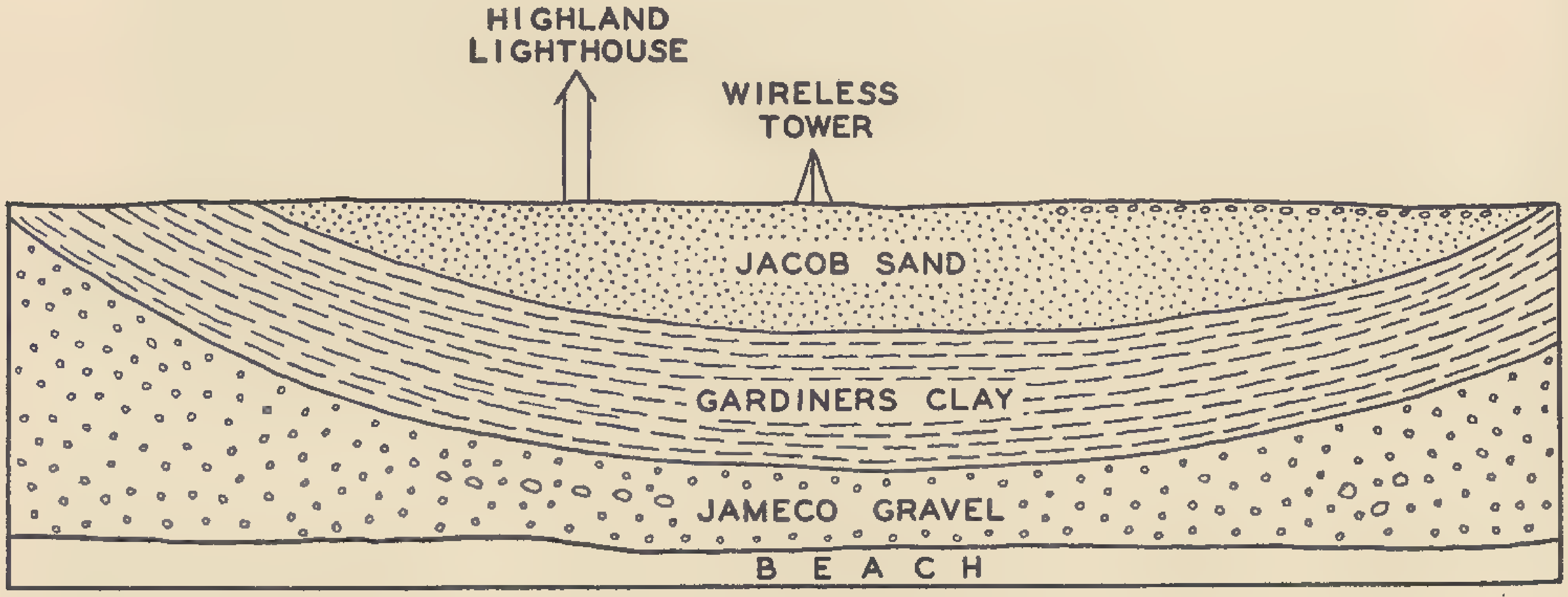

Fig. 20.— Section at Highland Light, in North Truro, showing the "clay pound" or supposed Gardiners clay resting on gravel identified by Fuller as Jameco gravel and overlain by sands that resemble the Jacob sand.

The bed of clay that crops out at Highland Light lies in a shallow syncline, the axis of which appears to trend south of west and to pitch in that direction, so that the clay is brought out beneath the North Truro plain to the bluff on the bay side between North Truro station and Truro, on the Pamet River. But the clay on the bay side is prevailingly sandier than the typical Gardiners clay, and it passes laterally into sand and gravel. At a point a mile south by east from Truro station there was exposed in the bluff, in 1916, the typical Gardiners succession, namely, gravel below a brownish clay less than 20 feet thick, and above that a fine yellow sand resembling the Jacob sand. The clay bed thickened toward the north, but the sand became gravelly. There is a downfold in the series and beds of clay extend along the bluff nearly to North Truro, but whether at the same or at a higher horizon cannot be ascertained because of the slumping of the cliff. The clay south of the sharp downfold may lie at the horizon of the beds of clay, gravel, and sand which on the ocean side rise up south of the "clay pounds" and show a clayey section beneath the large bed of clay at the lighthouse.

A lens of clay was seen in a fresh cut of the bluff about a third of a mile south of the Pamet River Coast Guard station in April, 1916. It presented a rounded termination on its northern border, suggesting that overthrusting had foreshortened the lenticular cross section, unless the whole appearance were due to the dislocation of a once more continuous layer of gray clay. This lens was 25 feet long.

These lenses of clay in gravel and sand lie below the horizon of the Gardiners clay, if that formation is represented by the clay at Highland Light.

Fully a dozen beds of blue clay are exposed about Chatham, and along the coast as far north as the north side of Pleasant Bay. The outcrops mapped on the bluff near Chatham Light, at the northeast end of Oyster Pond, and on the sides of a lakelet about a mile northwest of that pond fall into a line extending northwestward and marking either the outcrop of an eroded inclined bed of clay or the axis of a fold. The clay on the south side of the lake mentioned dips rather steeply westward under light-colored sand (Jacob?). In a railroad cut west of the south end of High Hill a sharp fold of clay and overlying sand dips eastward at an angle of 23°. This outcrop lies east of those on the banks of the lake and seems to show that an anticlinal arch brings up the clay along the line described. North of this outcrop, on the west side of Rider's Cove, there is another, and north by east of this is an exposure on the northern part of Nickerson's Neck. North of this outcrop there are exposures on the north shore of Pleasant Bay, on both sides of a small cove. There is also an outcrop of clay on the North Chatham shore about half a mile north of Allen's Point. The alignment of the necks and topographic features, including Great Hill, near Chatham, is due partly to erosion, but this erosion appears to follow the folding of older Pleistocene beds, including what appear to be the Gardiners clay, the Jacob sand, and the Herod gravel. Great Hill is possibly a syncline of Montauk till.

About half a mile west of Harwich railroad station, there is an exposure of reddish clay, which possibly lies at the horizon of the beds of clay here described. Mr. Gilbert Hart, my assistant, noted outcrops of clay under sand along the railway east of South Chatham at two points. This clay appears to be widely distributed under the southeastern part of Cape Cod in low folds, which here and there reach the present surface or lie a few feet below it.

On the north side of the Falmouth moraine, at an elevation of about 150 feet, on the northwest slope of Bourne Hill, in Sandwich, in the roadside there was exposed in 1916 some 6 feet of clay beneath glacial gravel and the surface till. This clay bed is well up in the morainal ridge and is probably a part of the outwash in front of the Wisconsin ice sheet.

At Yarmouth railroad station, in the low cut west of the branch track running to Hyannis, there was exposed in 1916 beds of clay in which boulders are either visible or are reported to occur. The section exposed follows:

Deposits at Yarmouth

	Feet
Sandy till with some boulders	4
Sharp yellowish glacial sand	6
Brownish boulder clay; larger boulders, 3 feet long	4

The surface at this point has been traversed by the Wisconsin ice and the top layer beneath the soil corresponds to the general sheet of Wisconsin drift in the Falmouth moraine of the district.

The bed of till noted above crops out north of the morainal ridge and cannot be far above or below the horizon of the beds of clay that crop out along the coast of the Bay or within half a mile of the coast where the overlying Falmouth moraine is relatively thin or absent.

Blue clay crops out along the south shore of Cape Cod Bay and is well exposed from West Barnstable railway station eastward to the brick-clay pits in a small valley about a mile east of the station. The beds of clay in the pits lie close to the level of high tide. The surface at the railway station stands nearly 50 feet above sea level. The beds of clay have evidently been eroded by glaciers since they were deposited. According to statements made to me in 1899 the beds of clay at the brick pits are underlain at one place at a depth of 18 feet by quicksand and at another place by gravel. The clay contains angular stones, the largest a foot in diameter, and is said to carry large boulders about 4 feet below the surface. In this respect the clay resembles the Montauk till rather than the Gardiners clay. Farther south the clay disappears beneath sand and sandy clay and is well stratified.

Probably the same bed of clay continues westward along the shore of the Bay and crops out opposite Sandwich, near the old glass works, where formerly bricks also were made. Rolls of clay were struck by workmen digging the eastern part of the Cape Cod Canal and the boulders found below the sand in the district were probably in this clay. These boulders appear to have been dropped from masses of floating ice, if not from glaciers. Such boulders occur in the brick clays at North Cambridge at a horizon that is presumably equivalent to the Gardiners clay. No boulders have been found in the clay at Highland Light and in the third cliff at Scituate in sections that are similar to those of the Gardiners formation on the islands, so that the clay at Barnstable and in the valleys of the Charles and Mystic rivers may lie either at the horizon of the Montauk boulder clay or at a lower horizon than the Gardiners clay. They may be the equivalent of one of the stony blue clays near the base of the Pleistocene section.

JACOB (?) SAND

The assumption that the clay at Highland Light represents the Gardiners clay involves the correlation of the overlying beds of yellowish fine sand with the Jacob sand on the islands to the southwest. Sandy beds also overlie the beds of clay about Pleasant Bay and in the brick-pits at West Barnstable. If, however, the boulder-bearing clays along the shore of the Bay represented the Montauk till these beds of sand should be regarded as Hempstead beds. Large tracts of sand and gravel overlie the clay along the south coast of Cape Cod Bay. These tracts lie beneath the veneer of frontal moraine which covers the district. Some reasons for regarding both the sand and the gravel as newer than the Jacob sand are set forth below.

MANHASSET FORMATION (?)

Herod Gravel Member (?)

On the islands the Herod gravel underlies the Montauk till or boulder clay, occurring very much as the Jameco gravel occurs beneath the Gardiners clay. The Herod normally overlies the Jacob sand, which may in places be gravelly. If the boulder clay in Barnstable is the Gardiners clay the overlying beds of gravel in the tabular hills along the coast of the Bay at the foot of the moraine represent the Herod member; but if the beds of clay are regarded as the equivalent of the Montauk till, the Herod would be found below sea level, and the gravel lying above the clay must be the equivalent of the Hempstead gravel. South of the frontal moraine, which consists mainly of sand, there is a broad expanse of sand and gravel that is evidently older than the outwash from the Falmouth moraine.

Montauk Till Member (?)

Along the south shore of the Bay from Barnstable westward to the Cape Cod Canal there are beds of clay that are said to contain large boulders, such as are characteristic of the Montauk till rather than the Gardiners clay as known on Marthas Vineyard, No Mans Land, Block Island, and Long Island. The clays about Pleasant Bay may not lie at the same horizon as those seen about Barnstable, but are probably part of the same deposit that underlies the southern part of Cape Cod at about sea level.

In the bluff on the south side of the entrance to Nauset Harbor there is an outcrop of till or clay containing striated stones and underlain by gravel and sand. This outcrop lies within the boulder-strewn area of the Falmouth moraine, but the bed of till appears to be in the older Pleistocene below the surface moraine. There is also a small exposure of stony clay in the low bluff at the Nauset Beach coast guard station. This bed is only 3 or 4 feet thick and overlies about 6 feet of brown clay. The entire section at this point appears to be a part of the Eastham plain, and is possibly newer than the section at the entrance of Nauset Harbor. Deposits of sand, gravel, clay, and pebbly till were probably laid down at all the glacial stages along the ice front, which probably advanced at times over its washed deposits and then retreated so as to produce alternations of stratified and unstratified deposits. The two sections described show that there are several beds of true stony clay till on the Cape and that their positions in the older Pleistocene succession can be determined only where the beds of clay or till are very thick and extensive.

Hempstead Gravel Member (?)

Beds of gravel overlie the blue clay in the southern part of Cape Cod in a position comparable with that of the Hempstead gravel, which lies upon the Montauk till in the islands. If the clay in the southern part of the Cape is the Gardiners clay the gravel and sand beneath the morainal outwash correspond in position to the Herod gravel, which lies beneath the Montauk tills.

Summary

The beds of gravel and sand that lie above the clay are evidently older than the Wisconsin outwash gravel in the southern part of the Cape and represent the Manhasset formation, which is composed of the Herod gravel member below, the Montauk till in the middle, and the Hempstead gravel member above. All three of these members are found on Cape Cod. In the plain on the south side of the Cape these beds of gravel and sand, where they are not covered with the outwash from the Falmouth moraine, show traces of erosion channels made by streams prior to the Wisconsin stage.

THE VINEYARD INTERGLACIAL STAGE

EROSION PHENOMENA

Before the Wisconsin ice advanced to Nantucket and Marthas Vineyard the outer line of islands and, presumably, the region north of them, were long subjected to normal fluvial erosion. On Cape Cod there are traces of a pre-Wisconsin topography on the plain in its south-eastern part and in the plains of Wellfleet and Truro. These plains lay in or near the interlobate axis of the ice sheet, where, as there was no erosion by ice and the glacial deposits were small, the older features have been but slightly masked by the Wisconsin deposits. The dissection of the beds of gravel and sand in the area about Chatham, in Harwich, and in Orleans evidently preceded the advance of the Wisconsin ice to Nantucket, because the ice-block holes occupied by the lakelets there differ from those farther west, about Falmouth, for they lie in channels cut in the folded beds of clay and sand of the pre-Wisconsin drift here referred to as probably the Montauk till of the Manhasset formation. The peculiar winding courses of these depressions are not like those excavated by moving ice, and they were evidently not the channels of subglacial streams, because they were occupied by stagnant ice left over from the Nantucket stage of the Wisconsin glaciation. Thus the unevenness of the plains of the Chatham district (except the outwash terrace, which was formed during the last advance of the ice of the Cape Cod bay lobe) dates back to an interval of erosion between the deposition of the Manhasset formation and the Wisconsin ice advance. Similar features may be seen in the highland plains of Wellfleet, where the deep channels or "hollows" are flanked by moraines and kettle holes, which show that these channels were in existence when the last ice lay over that region. Moreover, large boulders here and there on the surface, such as those seen near Highland Light, show that an ice sheet lay here after the topography had been outlined. These plains or terraces thus fall into two groups — the high-level Wellfleet plain and the low-level Chatham plain.

THE WELLFLEET PLAIN

The Wellfleet plain, which forms the highlands of the forearm of the Cape, is much dissected and is in places masked by moraines and kettle holes. Its highest points reach elevations of 140 to 150 feet north and south of the valley of Pamet River. Toward the west it declines to elevations of about 100 feet. It overlooks from Truro northward the lower plain of North Truro, which has an elevation of 60 to 80 feet and a surface partly masked and partly carved by glacial and stream action during the Wisconsin stage. Most of the deposits on it, however, are older than those of the Wisconsin stage. North of the clay pounds at Highland Light the lower, oldest beds in that region can be traced continuously northward into the bluffs of the lower plain — the Truro. The Wellfleet plain appears to have been deeply dissected by westward flowing streams before it was occupied by the Wisconsin ice. Some of the vales in this plain headed in land that stood east of the present cliffs of the Cape, but that is now washed away. The spaced erosion and the general parallelism of the channels do not resemble the creases on the margins of the outwash plains that were formed in front of the Wisconsin ice sheet on Nantucket and Marthas Vineyard. At a place in the Eastham plain where Fresh Brook enters the salt creek that occupies the greater part of a small valley there is a pamet[1] that is unmodified by glacial action.

Although it may be assumed that the stream erosion on the Wellfleet plain was the work of water that flowed out of the ice sheet during its advance in Wisconsin time, this assumption appears to be unwarranted, for the ice did not entirely melt during the interval between the Nantucket and the Falmouth substages, and the pamets were in existence when the ice sheets finally disappeared. The bottoms of these channels, like those of the channels about Chatham, lie below sea level and should be referred to the third stage of erosion — that is, to the Vineyard interglacial stage.

Great Hill, which stands northwest of Chatham village and rises to an altitude of 132 feet, may be an outlier of the Wellfleet plain. Some of the areas in the necks east of Orleans approach the 100-foot level and may be regarded as tracts that were not worn down to the level of the Chatham plain.

THE CHATHAM PLAIN

Most of the eroded and thinly mantled surface of the Chatham plain stands less than 80 feet above sea level. It lies within the Falmouth moraine, east of Orleans. The surface about Chatham village declines to levels below 60 feet and shows no trace of a break or cliff between a higher and a lower level.

A large tract in which the topography is similar lies in Harwich, south of Long Pond. Remnants of the Nantucket ice covered this tract so completely as to prevent the deposition of the sand and gravel that was washed out from the moraine in the Falmouth stage of the Wisconsin glaciation. The streams in this tract flowed in long, straight channels that ran between west of south and southwest. Here kame-like elevations 50 to 70 feet high are common, and some that stand farther north reach a height of 80 feet or more. Much of the glacial material here must be assigned to the Nantucket substage, when it was laid down around ice blocks that were afterward replaced by lakelets. Such deposits, however, are at many places thin or nearly absent, as shown by the older clays in cuts about Harwich.

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[1] A pamet is a long depression in a thick deposit of stratified gravel and sand. In its course and slopes it resembles a small valley formed by running water, but its sides and bottom have the forms of mounds and hollows produced by irregularities in the deposition of glacial drift, either ice-laid or water-laid. Most of these in Massachusetts occur in nearly parallel groups and occupy interlobate morainal tracts in the Wisconsin drift. In the Plymouth woods such depressions merge into lines of inosculating kettle holes, which are occupied by glacial lakelets.

Other features of the Vineyard erosion interval on the Cape are the channels and embayments cut in the Chatham plain, which were graded to a base level of erosion that lay below the present sea level. The relative position of this base level when the channels were cut cannot even be inferred from the depth of the channels that remain, for they occupy positions that must have lain well back from the mouths of the eroding streams. Shaler[1] recognized the pre-Wisconsin topography of parts of Cape Cod and drew a hypothetical map showing the old lines of drainage. The base-level to which this drainage system is related lies indefinitely below the present level of the sea.

NORTH TRURO PLAIN

(See Plate **25**, fig. 2).

The well-defined plain in the northwest part of Truro, including Pilgrim Heights, at the north end of the glacial part of Cape Cod, stands less than 80 feet above sea level along the western edge of the higher Wellfleet plain from Highland Light southward nearly to Pamet River. The escarpment between the two plains is a distinct topographic feature despite considerable dissection. The surface of this plain is creased by shallow channels of late Wisconsin streams, as noted by Grabau, but the material found above sea level consists of gravel, sand, and clay, which may be traced into the lower part of the beds that form the mass of the higher Wellfleet plain. The North Truro plain is therefore a bench or terrace cut back into the Wellfleet plain from the west prior to the last action of the Wisconsin ice or of the streams. There are practically no boulders on the surface, and except for the coastal sections one would infer from the surface features that the plain is wholly of late Wisconsin age. It seems necessary to correlate this terrace plain with the terraces that stand at heights of 60 and 80 feet in the southern part of the Cape.

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[1] N. S. Shaler, Report on the geology of Cape Cod, p. 516, fig. 86.

WISCONSIN GLACIAL DEPOSITS

The deposits of the Wisconsin stage of glaciation on Cape Cod consist of certain beds of sand and gravel, and probably also some of till, which were laid down along the south side of the Cape during the first advance of the ice to Nantucket and during times when stagnant masses of that sheet of ice were melting, as late as the second advance, which reached only the position of the morainal ridge that skirts the southern arm of the Cape. Practically all the boulders, gravel, sand, and clay in the high plains and morainal mounds from Woods Hole northward past Buzzards Bay and thence eastward to Orleans pertain to the second and last ice invasion. These two distinct groups of Wisconsin deposits are described below.

NANTUCKET SUBSTAGE

The terminal moraine of the Nantucket substage lay some 30 miles south of the Falmouth moraine. The deposits and the topographic features on Cape Cod pertaining to the Nantucket substage are widely spread south of the Falmouth moraine.

Practically all the kettle holes and glacial lakes of that region, even those that lie within the Falmouth moraine, represent the sites of blocks of ice formed while the stagnant ice of the Nantucket substage was melting. The block of ice that occupied the site of Great Pond, in the town of Barnstable, must at first have risen high enough above the surrounding surface to supply by its melting not only a considerable stream, which flowed from its southern border, but fans of gravel and sand that were built out from its side.[1]

One has only to fill these depressions in imagination with large berg-like masses of ice, which were more or less charged with stones and sand and which rose above the level of the plains of that part of the Cape, to gain a vivid picture of the landscape at the time the ice sheet of the second or Falmouth substage yet lay against the northern slope of its terminal moraine.

These ice masses lay in chains and groups that had rather well-defined directions. A remarkable chain extended across the plains in Barnstable from Pondsville southward to Great Bay, east of Cotuit, a region in which the back bays of the coast are ice-block holes. The northernmost depressions in this chain, known as the Cotuit ponds, are separated by transverse ridges supplemented by bars thrown up by the waves on the lakelets. Here a large mass was divided into three smaller ones and drift filled the channels between them. On the southeast side of the southern pond an ice-contact terrace and outwash plain shows that a sand plain was formed in a space left by the melting of the ice.

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[1] Woodworth, J. B., Some glacial wash plains of southern New England, Bull. Essex Inst., **29**, 1897 (issued in 1899), pp. 71–119. (See pp. 93–95, and fig. 4.)

Another group of ice-block holes in the town of Sandwich, near Farmersville, including Spectacle, Triangle, Lawrence, and Hog ponds, further illustrates the mode by which the remnants of the Nantucket ice sheet were broken up by the opening of channels that were filled with gravel and sand, here perhaps largely by outwash from the Falmouth ice front, for the frontal plain of that substage encloses these holes.

A lakelet in the bottom of one of these depressions may occupy a lower story, so to speak, in a group of depressions. On one or more sides of such a lakelet there is a terrace whose surface lies at the foot of a higher bank, or ice-contact slope, showing that the space around a large mass that had melted had been filled by gravel and sand to a certain height before the ice block disappeared. Such a terraced kettle or ice-block hole may be seen in Wakeby Pond, in Sandwich.

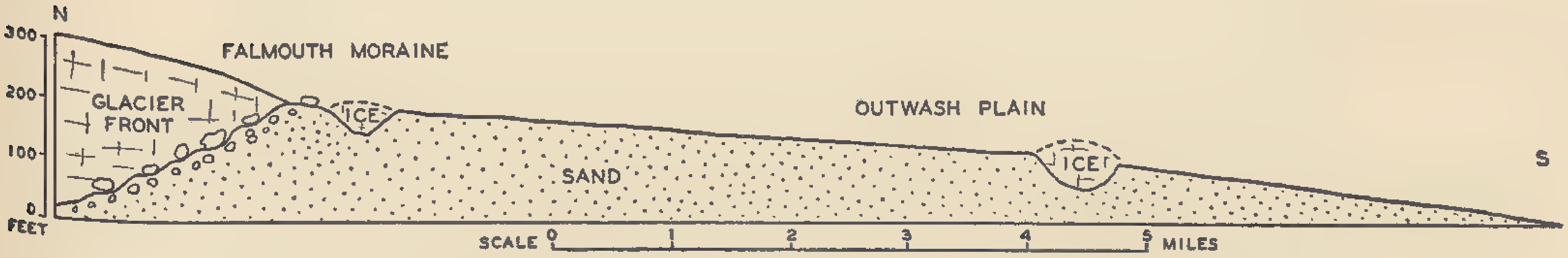

Fig. 21. — Section of Falmouth moraine and outwash plain, showing old ice blocks in sites of glacial lakelets.

The close alignment of the ice blocks and their somewhat regular spacing suggests that broad waterways existed between remnants of the ice sheet in the first clearly defined stage of its final disappearance and that cross channels were afterward formed by melting, so that the long ridges were broken up into huge blocks, roughly half a mile to a mile and a half across. The long axes of the holes, as shown by the shapes of the lakelets, trend southward through Falmouth, Sandwich, and Barnstable, though departures from this general trend are shown by ponds that extend southwestward. Farther east, in Yarmouth and Harwich, the southwestern orientation of the long axes becomes a pronounced feature, not only in individual ponds but in groups of ponds. In its northern half Bass river, a connected series of ice-block holes and channels, trends southeastward, but it turns abruptly at South Dennis. This orientation of topographic features was due to the structural control resident in the moving glacier or in the ground on which it lay. Along the lobes of many existing glaciers there are crevasses that stand nearly perpendicular to the front of the lobe, but in none of the stagnant glaciers in Alaska do such crevasses widen to form broad channels in which deposits of drift have accumulated. In the channels on the south side of Cape Cod such deposits were formed 25 to 30 miles back of the ice front while the ice was at its maximum extent, when it covered the northern half of the site of Nantucket. Certain ponds, such as those at the west base of Great Hill, in Chatham, occupy ice-block holes whose sides are in part formed of much older drift, showing that remnants of the ice there held open ancient channels in what is here called the Chatham plain. Chains of ponds and waterways on the south side of the Cape within these plains appear also to be old channels that were in part filled with more recent drift that gathered around masses of ice, which eventually melted and left depressions. The alignment of the lakelets and ponds may therefore be a reflection of the topography of the Vineyard interglacial stage just before the Wisconsin stage of glaciation. Such channels extend north of the Falmouth moraine in Orleans and are well shown by the trend of Town Cove. Lakelets did not lie in these old channels, because the ice was there deepest and thickest and therefore remained longest.

Estimates as to the thickness of the ice which stood in these holes depend on evidence as to whether the water supplied by the melting ice built up gravel fans or formed outflowing streams. Many existing depressions are shallow saucer-shaped pits, the ice in which may have been covered by gravel and sand. Such pits are found in Alaska.[1] Great Pond is flanked by fans of drift, which was probably derived from ice that rose above the level of the plain. The small, high tables of drift about Long Pond, in Brewster, appear to have had the same origin. From several ponds water now flows out through channels that are much too large to have been cut by the streams that flow in them. Mashpee and Cotuit rivers are examples of such drainageways. These shallow valleys appear to have been cut by streams that flowed through them when the melting ice in the ponds added water to the run-off arising from rainfall. Many lakelets have such excurrent channels, which start out much above the level of ground water. Ashumet Pond, on the line between Mashpee and Falmouth, is a typical example of this type of glacial lakelet. Whether the water of a lakelet formed an excurrent stream depended upon the height of the water table in the gravel and sand, for the lakelets and ponds may be regarded as great open wells. A depression that does not descend to the depth at which water stands in the sand remains essentially dry. Such dry kettles are found in the northern part of the outwash plain about Falmouth.

[1] Tarr, R. S., and Martin, Lawrence, Alaskan glacier studies, Washington, 1914, Pl. 76.

A chain of ice-block holes that are occupied by lakelets extends from the plain south of the Falmouth moraine into the higher ground of the moraine. Long Pond, in Falmouth, is a conspicuous example of this entanglement of remnant ice blocks of the Nantucket substage with the ice front of the Falmouth or second Wisconsin substage. The ice blocks in Spectacle and Lawrence ponds, near Farmersville, appear to have been pushed into by the Falmouth ice, as does also the block that gave rise to Great Pond, in Barnstable. The Mill Ponds in Brewster occupy a similar position, and numerous smaller ponds lie along the southern edge of the moraine, showing that the Falmouth frontal lobe deployed into a region that was still occupied by scattered masses of the Nantucket ice sheet.

Upham[1] has pointed out that the abundant supply of gravel and sand about the ice blocks which gave rise to glacial lakelets of this kind must have come from drift that lay well up in the ice sheet.

Masses of ice stood in the open ice-block holes south of the Falmouth moraine during the second ice advance of the Wisconsin stage and lasted without much change until the ice of that stage had disappeared; otherwise the outwash of sand and gravel from the Falmouth ice would have obliterated the depressions. The duration of the second or Falmouth substage was brief as compared with the duration of the remnants of the Nantucket ice.

On the south side of the Cape, in addition to the ice block holes of the Nantucket substage, there are a few hills of drift that rise above the level of the plain. Falmouth Heights is such a hill. It borders on Vineyard Sound, is about 40 feet high, and is evidently older than the low sand plain that surrounds it on the landward side. The bluff, which is now in part revetted by a sea wall, shows coarse cobbly drift and much glacial sand. Small boulders occur in the talus and on the beach. The deposit has all the internal characters of a torrential kame. Its form suggests that it was overrun by the Wisconsin ice sheet when that sheet advanced to Marthas Vineyard. It is early Wisconsin or older.

Two small till-covered areas lie at the entrance to Lewis Bay, south of Hyannis. The hill that rises above 60 feet at Hyannis Port appears to have been strewn with small erratics, more of which are now gathered in stone fences. The southwestern trend of the hill, parallel to that at Falmouth Heights, agrees with the trend of the buried channels of the plain and indicates that ice moved southwestward across this area during the Nantucket substage of glaciation. Squaw Island, just back of Hyannis Point, is also a low mound of till. Boulders on both sides of the drainage crease at Craigsville show that till lies either at or very near the surface. Great Island, whose southern part forms Point Gammon, is also a till-covered tract. Another small tract makes up "Fish Hills," called Harbor Bluff on the map, at the entrance to Hyannis harbor. All these till-covered tracts stand out because the sand of the plains on the north does not cover them.

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[1] Upham, Warren, Walden, Cochituate, and other lakes enclosed by modified drift, Proc. Boston Soc. Nat. Hist., **25**, 1891, pp. 228–242.

Large boulders lie at some places along the shore. Those south of Harwich have been noted by Julien.[1] There are small patches of till on the beach at the east entrance of Herring River; at Dennis Port; on the shore of Lewis Bay, east of Hyannis; at three points on the beach at Succonnesset and farther north, toward Poponesett Beach; and on Great Neck, in the southern part of Mashpee. These are tentatively referred to the Nantucket substage, but some or all of these deposits may be older.

It is not possible to distinguish the series of plains on the south side of the Cape that were formed or finished by the wash of sand from the remnant of the Nantucket ice from the series of higher plains farther north, which owe their origin to outwash from the ice sheet at the Falmouth substage; for the two series are so intricately interlocked that the attempt to make distinctions based not on difference in material but on slope, position, or slight differences of level would be long and laborious. A study either of the topographic map or of the ground shows that the large tracts in front of the high plains that form the southern border of the Falmouth moraine in Chatham, Yarmouth, and Barnstable were held open by masses of ice outside of the steep-sided ponds. Hundreds of small pits and saucer-shaped depressions too shallow to be expressed by the 20-foot contour interval of the topographic map dimple the surface, yet on the map these areas appear to be smooth seaward-dipping plains.

Amid all the variety of relief due to the deposition of gravel and sand between and around melting masses of the ice sheet in this region of broken plains there are no traces above the present level of the sea of its former action on the surface. It may therefore be inferred that neither at the time of the Nantucket substage of the Wisconsin ice nor since that time has the sea level here been higher than it now is. The ice blocks would have prevented tides and currents from sweeping sand into the kettles and holes in the plains, but after these ice blocks disappeared, tidal action upon these surfaces would have built deltas backward into ponds having excurrent channels, and waves would have thrown the sand into beaches at scores of places that were identical in exposure to those under which the beaches of the coast are found.

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[1] Julien, A. A., On the pebbles at Harwich (Cape Cod), Mass., and on rude arrowheads found among them, Science, new ser., **26**, pp. 831–832, 1907.

FALMOUTH SUBSTAGE

Falmouth Moraine

The Falmouth moraine forms the boulder-strewn belt of high ground (Plate **34**, fig. 1) that extends from Nauset Head, in Orleans, westward through the northern part of the main arm of the Cape to Manomet Creek, where it turns southwestward to Woods Hole and is continued in the Elizabeth Islands. In Orleans this frontal moraine is scarcely distinguishable except by its boulders and a slight thickening of the till over the older gravel and sand of the pre-Wisconsin glacial deposits on which it rests. The small glacial erratics on the surface about Chatham village and farther north, together with the deeply indented coast line, suggest that the ice front turned sharply southward at Orleans and that the edge of a lobate moraine covered the necks of land as far south as Chatham and thence ran out to sea. This part of the frontal moraine contains little drift in the angle between the off-shore lobe just mentioned and the lobate moraine that runs westward to Buzzards Bay. Just west of Orleans, however, the moraine becomes higher and thicker. The thickness of its beds of till or boulder clay increases, as well as the thickness and breadth of the outwash sand and gravel. From this point westward the outwash plain increases in size through the towns of Brewster and Dennis. They are highest and broadest just where the Cape peninsula is widest. In Yarmouth and eastern Barnstable the moraine diminishes in breadth and continuity and the confronting plain is correspondingly low and narrow, the change occurring nearly in the middle of the arc formed by the ice front that lay between the interlobate axis traversing the eastern arm of the Cape and that traceable from Plymouth to the angle near the Cape Cod Canal. West of Barnstable village the morainal belt gradually rises in height from 100 feet to more than 200 feet and reaches a height of 207 feet in Bourne's Hill, south of Sandwich, the highest point in the Falmouth moraine.

The highest points on Marthas Vineyard, Prospect Hill (308 feet) and Peaked Hill (311 feet), in the Nantucket moraine, owe their height almost entirely to older formations, whose topography was determined chiefly during the Vineyard interglacial stage. Manomet Hill, the highest point on the west coast of Cape Cod Bay in the Plymouth interlobate moraine, has an elevation of 394 feet. The hill is covered with till, but underneath the till there are beds of stratified gravel and sand that reach a height of about 250 feet above sea level where the State road crosses the northern spur of the hill. The approach of the summits of the pre-Wisconsin deposits to a height of 300 feet suggests a former base level at that height.

Road cuts on the northern slope of Bourne's Hill expose stratified beds of gravel, sand, and clay under a thin veneer of till, generally less than 4 feet thick. The mass of the hill is probably made up of outwash from the ice front.

From Bourne's Hill westward and southwestward through the town of Bourne the moraine forms the iceward border of a great outwash plain that is backed by a high ice-contact slope having a morainal topography and a surficial cover of thousands of granitic boulders, many of them gathered in huddles. The Manomet Creek depression, which is followed by the Cape Cod Canal, skirts this ice-contact border as a deep fosse separating the Falmouth moraine at the interlobate angle from the huge mass of drift on the north, in the Plymouth interlobate moraine. From Pine Hill, in Bourne (altitude about 260 feet) the morainal mounds slope southwestward and the plain on the east slopes southward, toward the Sound, at a steeper grade.

In this higher part of the Falmouth moraine the deeper cuts show that stratified sand is the chief constituent of its mass. The till varies greatly in thickness from place to place. Its greatest thickness is exposed in borrow pits 20 or 30 feet deep, but the till and coarse waterworn cobbly drift must form a very small part of the total mass deposited by outpouring streams at the front of the ice. Here as in areas farther east, in Brewster and Barnstable, masses of the Nantucket ice sheet remained while the great fan of outwash sand was deposited. Some of this sand was laid down in front of the ice, particularly in Falmouth, where Long Pond, now the town reservoir, extends from the plain halfway through the frontal moraine.

Many small sections exposed along the ice-contact face of this moraine indicate that the ice kept pushing on the sand deposited immediately at its front, advancing upon it one to three miles, as is well shown at the interlobate angle southeast of the village of Bourne. The morainal ridge at Woods Hole, as indicated by the mode of development of the moraine farther northeast, must also be only superficially composed of bouldery till. Like other parts of the Falmouth moraine it was doubtless laid down from ice masses at the Nantucket substage. At many places these ice masses appear to have served as barriers behind which outwash streams built up high-lying masses of sand and gravel. (Fig. 21).

The Outwash Plain

The impressive feature of the Falmouth substage is the great fan of outwash sand in the towns of Sandwich and Falmouth. This fan spreads out from the boulder-strewn ice-contact surface on the north, which stands at an elevation of 200 feet or more above the sea. Between the 200 and the 160 foot levels this fan slopes southward and southeastward for a short distance at the rate of about 100 feet to the mile. It stands behind the sites of the outlying ice blocks that gave rise to Snake Pond, at Forest Dale, and the chain of waterless kettle holes that lie at the east base of Pine Hill. This fan appears to have been the last part of the sloping plain to have been deposited at the ice front. From Snake Pond southward the slope is gentler but somewhat difficult to generalize upon because tracts of lower ground appear to have been held open by remnants of the Nantucket ice. South of the belt of ponds in the latitude of Hatchville, in Falmouth, the surface is channeled by stream creases, which are found along the southern border of the fan between Falmouth and the vicinity of Waquoit Bay. The bottoms of the widened-out lower courses of these creases lie below sea level and form a series of beach-barred lagoons whose longer axes are perpendicular to the coast line, like those bordering the outwash plains of Marthas Vineyard and Nantucket.

North of the Falmouth moraine, along the shore of Cape Cod Bay, there are a few till-covered morainal tracts, such as Town Neck and Scorton Neck, in Sandwich, and Nobscusset Point and Quivet Neck, which rise nearly to a height of 80 feet, in Dennis. Sections in cliffs or artificial cuts show that these moraines are composed of beds of stratified gravel and sand. Precisely similar low-lying areas lie inside of the moraine skirting Buzzards Bay and forming so-called ''necks,'' or even islands, at North Pocasset, near Cataumet, and between North Falmouth and West Falmouth. Near North Falmouth there are no boulders on the surface, which has the form of a terrace of stratified sand that stands 60 feet above sea level. The associated boulder-strewn tracts, some of which are higher, are obviously older than the moraine, yet this terrace shows a good ice contact at Cedar Pond and just north of it, along the inner part of Cataumet harbor, and is probably a late outwash of sand from the retreating ice front. This terrace was made above sea level.

THE INTERLOBATE MORAINAL AREA

The Eastham Plain

North of the town of Orleans there are deposits of drift which have been regarded by some as more recent than the Falmouth moraine. Chief among these deposits is the plain at Eastham, which filled in what may have been a depression between the moraine at Orleans and the "table-lands of Eastham," in Wellfleet, before the ice began its retreat.

This plain is separated from the Falmouth moraine on the south by a narrow belt of kames that extend across the Cape. The knobs and basins of this plain are well shown about the hamlet of Eastham Centre and along the coast just north of Nauset Beach lighthouse.[1] The kames in this plain were deposited in the presence of ice and were originally probably an extension of the creased plain on the north. Grabau first and Wilson later presented the view that the Eastham plain was built from an ice mass lying east of the present coast of Cape Cod by streams flowing westward, just after most of the ice had melted away from the site of the moraine at Orleans.

The Eastham plain (also called the "table land of Nauset") presents a relatively even crest to the Atlantic waves at its cliffed edge. From an elevation of about 70 feet at its eastern margin the plain slopes westward and merges on the south and southwest into a field of kames and ends rather abruptly on the bay side in deeply indented knobs of sand and gravel. Its surface is traversed by creases made by running water. The plain lies north of the bouldery moraine about Orleans and south of the broken higher plain in Wellfleet, so that its position and its slope toward the continent and away from the sea excludes the supposition that it was modeled by the action of the sea.

The gravel and sand in the eastern bluff have been stratified by the action of water except at the south end of the bluff, near the Coast Guard station, where there is a bed of what appears to be till containing small pebbles and subangular stones.

Grabau and, later, Wilson appear to have assumed that this deposit of sand and gravel was laid down later than that found on the high plain farther north. Although the section along the cliffs was not entirely free from talus at the critical place at the time of my visit, it seemed that the beds on the seaward side of the Eastham plain may extend northward in continuity with the beds of the high plain in Wellfleet. If the beds of the Eastham plain were laid down later an unconformable contact should occur at the junction of the two plains where the surface of the ground changes its level. The somewhat similar plain that forms Pilgrim Head, at the north end of the Cape, is obviously a plane of erosion, and the gravel under the Eastham plain may have been laid down in the same manner at nearly the same time. The creases here are of the type formed by streams carrying little or no sediment and not heavily loaded distributary wandering streams, such as are found on deltas and alluvial tracts that are being actively aggraded.

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[1] The two lighthouses shown on the topographic map of 1887 are gone. On October 23, 1910, the north light stood 16 feet back from the summit of the cliff and on August 7, 1916, the lighthouse tower, whose base was about 15 feet in diameter, had fallen into the sea and the cliff was about 10 feet farther back than the site of the tower. A new light stands somewhat back from the present cliff.

Wilson[1] supposed that the Wellfleet high plain was formed by glacial streams just before the Eastham plain was formed. He held that, at his Wellfleet stage of Lake Shaler, the site of the Eastham plain was occupied by a tongue of ice that extended eastward from an off shore lobe of the ice sheet. This explanation of the kame field between the till-covered ground in Orleans and the creased plain north of it overlooks the probability that ice from the Falmouth substage remained there in stagnant patches. Abundant evidence of the existence of such remnants of ice is found in the lakelets in the moraine, such as Cliff Pond and the neighboring ponds in Brewster. The ice certainly stood on the sites of these ponds until the end of the Falmouth glacial substage. The remnants of ice about Eastham Centre were probably parts of the interlobate ice at the Falmouth substage. Most of the ice on the site of the unbroken plain had no doubt then melted except that in the creases about Eastham. The clear evidence that the water which formerly discharged across the plain in the creases, the necessity of admitting the existence at this time of ice on the east side of Cape Cod and in the depressions and ice-block holes in Chatham, Orleans, Brewster, and elsewhere in the low places of the moraine as far west as Sandwich appears to permit no escape from the theory of Wilson that the water which gathered in the space vacated by the ice back of the moraine found exit from the ice-barred growing crescent in the southern part of the site of Cape Cod Bay to a lower level through the Manomet channel or fosse.

To the water thus confined between the moraine and the receding ice front in Cape Cod Bay Wilson gave the name "Lake Shaler." The water level of this glacial-dammed lake, whatever may have been its extent, was controlled by the sill of sand in the Manomet fosse at Sagamore, which stood nearly 32 feet above mean low water in Buzzards Bay and more than 34 feet above mean low water in Barnstable, or Cape Cod Bay, or a little more than 25 feet above mean sea level.[2] This col is 27 to 28 miles south by west of the western limits of the Eastham plain. The bottom of the Manomet valley is composed of stratified drift showing signs of erosion by running water subsequent to the melting of the ice sheet in the fosse. Manomet River, which drained the glacial lakelets in the interlobate moraine, enters the fosse at North Sandwich and has cut a channel below the old glacial level of the stratified drift, forming a low terrace. At the west end of the fosse, on the shore of Buzzards Bay, the mouth of the river is bordered by sand flats that appear to have been formed in glacial time. We may therefore suppose that water once discharged from the basin behind the Falmouth moraine across the divide in the fosse to lower ground in the depression occupied by Buzzards Bay.

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[1] Wilson, J. Howard, The glacial history of Nantucket and Cape Cod, pls. 36–37. New York, 1906.

[2] Report of the Joint Committee of 1860 upon the proposed canal to unite Barnstable and Buzzards Bays, Public Document No. 41, pp. 26, 31. Boston, State Printers, 1864. This report includes a profile along the line of the proposed canal and a small-scale hachured chart.

The height of the water level up to which the Eastham plain was constructed, in Grabau's view of its origin, is not readily determined. The eastern cut edge of the plain at the grass line on the cliff obviously does not indicate the water level on either the old view that such plains were formed entirely under standing water or on the modern view that outwash plains of this kind are formed above the level of standing water. According to the old view, as the plain originally extended farther east and rose in elevation in that direction, the water level would have to be put at an indefinite height. The summit of the cliff stands somewhat below 80 feet. The North Eastham railroad station, which stands about midway across the southern part of the plain, in the upper part of the stream creases, stands at an elevation of 69 feet. In the areas west and northwest of this station the western edge of the plain proper accords roughly with a water level between 20 and 40 feet, but at some places, as west of the Methodist Camp Ground and on the coast near Fresh Brook, where the plain is now narrowest, its western edge bears knobs of drift that have steep ice-contact faces on the west, showing that they were formed in the presence of masses of ice. The plain may have been built up by streams that discharged water into the site of the Bay at a height about 30 feet above the present sea level, but the stream creases descend to and below the present sea level in the area around Fresh Brook. These stream creases were formed when the load of sediment had fallen off and the water discharged from the ice was cutting down the plain to a lower base level than that at which it was constructed. The streams at this stage could not have discharged through the Manomet fosse into the Buzzards Bay region but must have found some point of escape out of the bay at a lower divide in the morainal barrier on the south, for the deep channel of Pamet River and the now open bay on the north were then probably closed by the ice sheet. The only passage sufficiently low to conform in height to these creases is that from Boat Meadow Creek through Jeremiah's Ditch into Town Cove, in Orleans, in the interlobate axis, where water may have found its way out. It would be difficult, however, to sustain this view by pointing out any effects produced by water discharged along this course when the creases were being sunk into the surface of the Eastham plain. Lake Shaler is not marked by shore lines and must have been rather small and of brief duration at the stage of crease-cutting on the Eastham plain.

North Truro Plain

Intimately connected with the Eastham plain by reason of its similar elevation and the nature of the creases that dissect its surface is the North Truro plain, which terminated the glacial deposits of Cape Cod at Pilgrim Heights. This plain or terrace was made by the erosion of the beds that form the west edge of the Wellfleet high plain from Highland Light southward. A dissected escarpment separates the two plains along a southward-trending line from Highland Light nearly to Pamet River. This escarpment is not, as Wilson supposed, an ice-contact slope; it is an old erosion cliff that was greatly modified by stream action and glaciation. It is one of the most puzzling features in the topography and glacial history of Cape Cod, and it has no counterpart in the entire region except, perhaps, in the Plymouth region about Manomet Hill. The surface of the North Truro plain is creased, as Grabau and Wilson have noted, by very late Wisconsin streams, which discharged from the ice that lay around the eastern, northern and probably the northwestern border of this plain. When and by what agency was the North Truro plain cut down nearly to its present level, which lies below that of the higher plains on the east and south? At what stage of the ice retreat were the creases on the surface of the plain produced, and in what direction did the water escape to the sea?

The plain was formed by the erosion of a once higher mass, the beds of which are seen in the cliff at Highland Light. It was formed after the pre-Wisconsin deposits were laid down in the Wellfleet tract, because the valleys which intersect those deposits are traceable across the North Truro plain. These valleys in the region south of Highland Light are well shown by the topographic map. If the North Truro plain was cut back after the "hollows" or valleys of the Pamet River type were formed the "hollows" should have been filled to the level of the plain, even if they were afterward partly re-excavated when surface water ran in the creases on the plain and elsewhere. This plain appears to have been formed just before the Wisconsin stage of glaciation. It was probably once much wider and longer. Coarse gravel near Wood End, on the spit at Provincetown, indicates that this spit stands on a shoal that may represent an island which has been reduced to sea level during the present stand of the sea, when the cliff on the west side of the North Truro plain was cut. (Plate 25, fig. 2.) The plain probably did not extend west of the line of beach between Race Point and Wood End, because the sea floor there suddenly drops to depths of 24 to 28 fathoms. It is not known whether the original plain was cut back into the older Pleistocene deposits at Highland Light by glacial streams that discharged southward across that part of the Cape in advance of the Wisconsin ice sheet or whether it was formed at sea level by wave action during the latest part of the Vineyard interglacial stage.

Most of the creases on the North Truro plain drain westward. Fine examples of these creases may be seen at the North Truro railroad station, where they come down from the clayey ground at the western base of the hill on which the Highland light stands. A deep crease springs out from the air, so to speak, at the crest of the cliff south of the lighthouse and follows closely the line of the escarpment between the upper and the lower plain. Other short creases, which have curving courses, lead down the northeastern side of the plain, showing that the streams flowed in that direction, unless we may suppose that these creases were formed by the run-off from the plain, an unlikely supposition, because of the freedom with which rainwater soaks into the sand and gravel north of the clayey tracts west of the lighthouse. The bottoms of these creases, like the bottoms of those of the Eastham plain, were as low as the present sea level, and the streams that occupied them probably found their way between the ice and the gravel banks and joined those of the Chatham drainage system, which appear to have been contemporaneous. The structure of the beds in the North Truro plain and the extension of these beds into those at Highland Light, notwithstanding the community of level of the two plains, does not seem to warrant the assumption that a glacial lake was held in elsewhere by the glacier.

The Wellfleet Plain

There is abundant evidence in kettle holes and in downsunk beds of stratified drift in the outer coastal section that at least the superficial parts of the southern and eastern divisions of the Wellfleet plain were shaped by the Wisconsin ice and that deposits were laid down from that ice either directly or by the action of water. Kettle-hole topography is typically developed around the lakelets south of Pamet River. What appears to have taken place is as follows:

1. Deposition of a foundation of stratified material, including the beds at Highland Light that suggest the Jameco gravel, the Gardiners clay, the Jacob sand, and possibly the lower part of the Manhasset formation.

2. Deposition or erosion of a then more extensive tract and, after its surface had been shaped by deposition or erosion, its dissection by streams flowing to a base level that is now submerged. The heads of most of the stream valleys then lay on a divide east of the present coast line.

3. The Wisconsin ice sheet then advanced over this tract, filling depressions with ice in the interlobate axis between the offshore South Channel lobe and the Cape Cod Bay lobe. In the interlobate axis of two such lobes the motion of the ice and its erosive power is at a minimum.

As the glacier melted, masses of the ice were left here and there in low places, and the spaces about them, between the ice and the hillsides, were filled with gravel and sand and some of the older valleys were more or less blocked, so that many of the depressions in this glacial field, where pre-Wisconsin glacial deposits and valleys are partly masked by Wisconsin ice effects, are very complex.

The "hollows" in this region are named and described in Blunt's American Coast Pilot.[1] The first and northernmost of the "hollows," known as Dyer's hollow, opens on the east coast of the Cape at a point 1½ miles from the lighthouse, at the clay pounds. No. 2, Harding's hollow, which is 1½ miles south of Dyer's hollow, is blocked by sand just north of Pamet River. No. 3 is at the head of Pamet River, and No. 4, known as Brushy hollow, which is three-fourths of a mile south of the head of Pamet hollow, is a narrow vale that runs into Pamet hollow. No. 5, 3 miles south of Brush valley, known as Newcomb's hollow, lies east of the head of Herring River, in Wellfleet, and is a quarter of a mile wide. No. 6, which is half a mile south of Newcomb's hollow, is known as Pearce's hollow. No. 7, Cohoon's hollow, is half a mile south of Pearce's hollow. No. 8, Snow's hollow, is 2 miles south of Cahoon's hollow. No. 9 is Fresh Brook hollow, the name Fresh Brook appearing on current maps. No. 10, Plumb valley, is 2½ miles south of Fresh Brook, at a point just north of the Nauset Beacons on the present map. These hollows afford opportunities for castaways on the beach at the back of the Cape to reach places of refuge and the houses of the inhabitants, so that they need not attempt to climb the steep sand and gravel bluffs, which for long distances are unscalable.

PLYMOUTH INTERLOBATE MORAINE

As the retreating ice sheet in Cape Cod Bay melted and permitted the drainage from the lobe lying east of Cape Cod to discharge westward into the basin just vacated by the ice, so the lobe lying west of the Plymouth interlobate axis appears to have melted out faster than the lobe lying in Cape Cod Bay, for there are similar high plains of stratified drift that slope westward and southwestward from the axis of the lobe into the basin vacated by the ice of the Buzzards Bay lobe. This earlier melting of the ice on the western sides of the interlobate axes in these two fields may mean that the ice was thicker and maintained longer, more vigorous advance over the Bay of Maine than over southern New England. This difference may not have arisen so much from inequality in the snowfall in the eastern and western parts of northern New England and the adjacent gathering grounds on the north as from the fact that, in Vermont and New Hampshire, the ice sheet encountered high mountain barriers that restricted its flow to the southern part of the field after the Labrador ice sheet began to melt. Farther east, over the site of Maine, broad lowlands stretched between the White Mountains in New Hampshire and Mount Bigelow, and between Mount Bigelow and Mount Katahdin. Another result of this freer flow of ice across Maine and east of Massachusetts is the apparent extension of the ice front, at least at the Nantucket substage, southeastward from Nantucket over Nantucket shoals and Georges Bank.

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[1] Blunt, Edmund M., The American Coast Pilot, 11th ed., pp. 71–74, 1827; New York, also 13th ed., pp. 179–183, 1837.

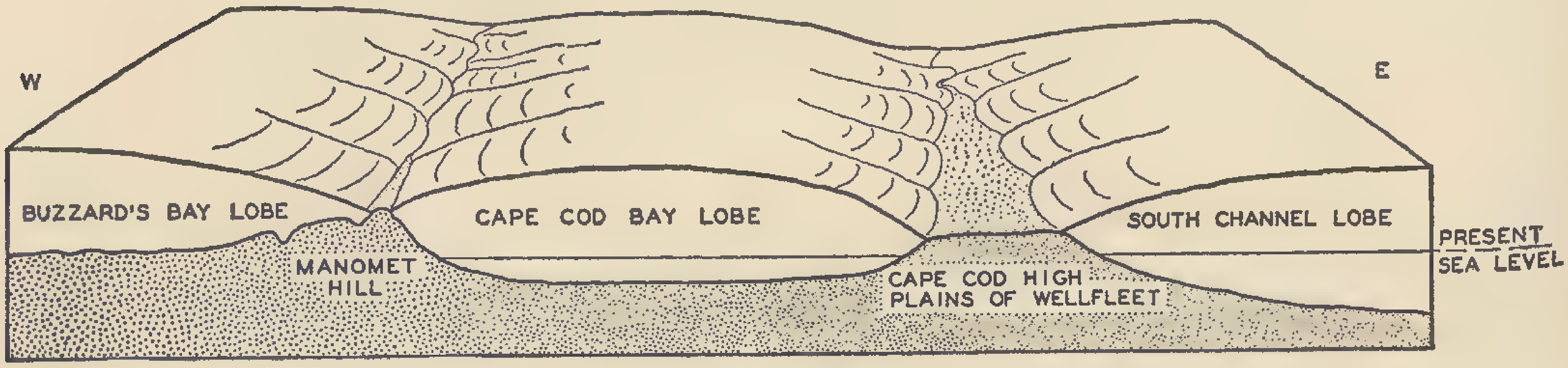

Fig. 22.— Theoretical cross-section of Cape Cod interlobate axis, Cape Cod Bay, and the Plymouth interlobate axis, with the Wisconsin ice sheet at the Falmouth substage.

The accompanying theoretical cross section (Fig. 22) in the latitude of Manomet Hill near Plymouth and the high plain near the Highland Lighthouse shows the relation of the ice sheet to the glacial formations before the ice sheet disappeared from the vicinity of Cape Cod Bay. Some such relation between the lobes of the ice sheet and the deposits made or left in the interlobate axes out of the path of maximum motion and most effective erosion of the ice began to give shape to the features of the land in the earlier ice advances.

POST-GLACIAL OR RECENT CHANGES

Cape Cod more than any other part of southeastern New England shows the changes due to the ravages of the sea since the glacial epoch. As the changes in the inland part of the area are insignificant compared with those that occurred along the shore, they will be considered later.

Changes in the Shore Line

The east coast of Cape Cod is somewhat protected from the attack of the sea by the great shoal known as Georges Bank, which lies southeast and east of the Cape at distances of 80 to 140 nautical miles. This shoal breaks the force of seas running from the east and southeast, but the Cape is exposed to the full force of northeast storms, which have a fetch of more than 250 nautical miles measured from the southern prong of Nova Scotia, and of a much greater fetch measured from the Bay of Fundy. Since glacial time considerable land has been lost on the east coast and the outline of the coast has been reduced to its present form, in which irregularities have been cut away to form a graceful curve. This cutting has been accompanied by the building up of great hooks and spits of wave-washed sand encumbered by dunes formed by the wind that sweeps the beaches. The submarine contours off the east coast of the Cape conform to the curvature of the shore line down to the depth of 24 fathoms. Those that lie at greater depths, south of Nauset Light, do not show like conformity. The curvature of the coast line increases westward as the exposure of the shore to the northeast storms increases, until at Highland Light the coast trends about 50° west of north. It turns within two miles to 70° W. on the bar that extends the Cape toward its northernmost reach, where it recurves to the southwest toward Race Point. The contour of the sea bottom below a depth of about 30 fathoms suggests that the original trend of the Cape did not differ much from its present trend from High Head as far south as Chatham.

As the submerged ridge between the north end of the Cape and Stellwagen Bank lies at a depth of about 24 fathoms, the land probably did not extend out beyond that depth, although the shore line may have been shifted inward by the erosion of the bottom or outward by deposition. At and off the headland of the Cape an old shore line lies 5 miles from the present shore. The nature of this headland of interlobate morainal material indicates that along the old eastern shore line there was an embankment or ice-contact slope along which the surface of the Wellfleet and Eastham plains dropped to a lower level, such an embankment as the mass of drift that skirts the west coast of Cape Cod Bay and forms an irregular wall of drift that rises above the present sea level. An estimate of the height and the extent of this outer bank may be made by a theoretical reconstruction of the Wellfleet and Eastham plains on a hypothesis supported by a comparison of such deposits — namely, that the Eastham plain at its original summit along the ice contact rose as high as the Wellfleet plain. Assuming that the higher plain stood at an altitude of 120 feet at its iceward border, as it does just north of the Eastham plain, the eastward rise of the Eastham plain would reach this altitude at a distance of about 3 miles off the present coast. This estimate is of the same order of magnitude as that reached by Davis.[1] If the assumed rate at which the coast was cut back approximately during the present stand of the sea holds good, this work could hardly have been begun more than about 3,150 years ago. As the minimum estimate of the time since the ice sheet disappeared is more than twice this number of years and as the maximum is many times longer, the Cape would now have been nearly cut away by the sea if some cause had not prolonged its erosion. If the sea began its work when the land stood about 30 fathoms higher than it now stands in relation to sea level in the latitude of the middle of the arm of Cape Cod, the discrepancy may be accounted for by assuming an attack of the sea, brought about after a period of subsidence, on a prism of land that lay between the initial plane of marine erosion at the end of the glacial epoch and the present higher plane.

Gulliver [2] describes Cape Cod as ''a winged beheadland which projects far into the sea, so that the wings do not extend across the bays on either side.'' Davis [3] has considered at length the change from the presumable original glacial outline of the land to its present form under the action of the sea. Within historical time the headland has receded more than a third of a mile. On the south, in the zone of the winged bars of Chatham, small islands of glacial drift have disappeared. Mitchell [4] gave an account of these changes in a report concerning Nauset Beach and the peninsula of Monomoy,[5] and a brief summary of them is given by W. C. Smith.[6] From these and other sources of information it appears that at the time of the American Revolution Nauset Bar lay farther out than it now does and that there was an open lagoon between it and Nauset Head.[1] Until the great storm of November, 1730, there was an opening in this bar into Pleasant Bay at a point east of Strong Island. South of this opening a bar extended southward toward Chatham. Inside of this bar, near Allen's Point, lay Ram Island, which appears to have been enclosed on the north by the hook of the bar of Champlain's chart which joined the land at North Chatham. Ram Island, Cotchpinicuit or Scotchpenacot, as it was known to the aborigines, is shown on Des Barres' chart as lying east by south of Allen's Point. Mitchell[2] describes the island as shown on the first topographical map by Gluck in 1847 as then having an area of 13 acres, an elevation at some places of 20 feet, and some kind of building on it. A breach in the beach lay directly before the island, so that it was exposed to storm waves, but it continued to be used as a pasture down to 1851, when the Minot's gale washed it away, though traces of it could be seen for a few years later; but in the topographic survey of 1868 it could not be found.

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[1] Davis, W. M., The outline of Cape Cod, Proc. Am. Acad. Arts and Sciences, **31**, pp. 302-332.

[2] F. P. Gulliver, Shoreline topography, Proc. Am. Acad. Arts and Sciences, **24**, 1899, p. 213.

[3] Davis, W. M., The outline of Cape Cod, Proc. Am. Acad. Arts and Sciences, **31**, 1896, pp. 303–332.

[4] Mitchell, Henry, Nauset Beach and Monomoy peninsula, U. S. Coast Survey Report for 1871. Appendix 9, pp. 134–143, Sketch No. 35.

[5] For a list of the 39 different ways in which this aboriginal name has been spelled and pronounced, see William C. Smith, A History of Chatham, Part I, p. 1, footnote, Hyannis, 1909. Monomoit and Monomoy are variants of the same name. Monomoy is now restricted to the beach south of Chatham.

[6] Smith, W. C., A history of Chatham, Part I, pp. 6–11, 1909, with plate reproducing part of Champlain's map of Fort Famine showing the beach at Chatham in 1606.

Whiting[3] states that the Minot's lighthouse gale, which occurred in the middle of April, 1851, breached the outside bar at Nauset for 500 feet. The channel thus produced, which was 11 feet deep, remained up to 1867.

Numerous changes have taken place in the position and extent of the bar and the openings at Chatham since reliable charts of the locality were made. In Des Barres' time the inlet had the general form shown on the chart of 1887, except that the Monomoy Beach bar broke off from the beach flat south of the inlet and joined the land in front of the village, about as it did in 1915-16. In an easterly gale on November 15, 1871, the bar opposite Chatham lights was broken through (Plate **34**, fig. 2.) This breach appears to have rapidly shifted southward by the wearing away of the north end of Monomoy Beach and the southwestward building of the Nauset Beach, which according to a survey made in January, 1873, had joined the mainland near Chatham lights. For some time after the gale of November 15, 1871, the bluff near Chatham lights was exposed to the sea. Later the bar was re-formed in the manner shown on the chart of 1887. Since that time the hook on the north side of the inlet has grown southward about a mile. In 1916 the inlet was correspondingly south of its former position, and the Monomoy Beach joined the land at Chatham.

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[1] Mitchell, Henry, Additional report on the changes in the neighborhood of Chatham and Monomoy, U. S. Coast Survey Rept. for 1873, Appendix 9., pp. 103–107. Mitchell's first report was also printed in the Seventh Annual Report of the (Massachusetts) Board of Harbor Commissioners, House No. 65, Jan. 1873, Boston, pp. 94–108, 1873. Townsend, C. H., Notes on an early chart of Long Island Sound and its approaches, U. S. Coast and Geod. Survey Rept. for 1890, Appendix No. 20, pp. 775–777; illustration No. 71 reproduces Captain Southack's (?) chart of Cape Cod. Mitchell, Henry, Monomoy and its shoals, Ann. Rept. of the (Massachusetts) Harbor and Land Commissioners for 1886, Public Document No. 11, Appendix A., pp. 37–46; with map showing changes in Nantucket Sound from 1784 to 1885, Boston, Mass., 1887. Des Barres, Joseph F. W., The Atlantic Neptune, London, 1774–1781, **3**, charts of the coasts and harbors of New England, from surveys taken by Saml. Holland . . . Survr. general . . . and Geo. Sproule, Chas. Blascowitz, Jams. Grant and Thos. Wheeler . . . for the use of the royal navy of Great Britain.

[2] Report concerning Nauset Beach and the Peninsula of Monomoy.

[3] U. S. Coast Survey Rept. for 1867, p. 157. For an account of the "Lighthouse" storm of 1851 see Sidney Perley, Historic storms of New England, Salem, 1891, Chap. 70, pp. 302–310.

The swampy tract between Chatham and Morris Island is represented on Champlain's chart as an open passage which, according to Mitchell, became closed between 1752 and 1772. In 1916 the tide was flowing across the swamp and bar on the north side of the island.

Monomoy bar, on Monomoy Island, undergoes frequent changes. Again resort must be had to the reports of Henry Mitchell[1] for an account of it, from 1784 to 1885.

From this account it appears that the south end of Monomoy has shifted west ~~east~~ward as if it had fallen back with the retreat of the headlands on the north, and the southern tip has advanced southward much more rapidly. During the first period of accurate surveys of the position of the south point, between 1840 and 1853, the point gained in southing only about 140 feet. During the next three years, between 1853 and 1856, the point gained 509 feet to the southwest at a rate of 170 feet a year. At the time of the next determination of its position, in 1868, the point was about 2,123 feet farther southwest, an advance made in 12 years at the rate of about 175 feet a year. In June, 1886, the point has grown southward, but at a slower rate, 22½ feet a year. Mr. Mitchell concluded that the longshore drift from points north of Chatham became lodged somewhere north of Monomoy. It also became evident that the growth of the flying beach was subject to periods of maxima and minima of change.

Between Monomoy and Great Point, the corresponding flying beach at the entrance to Nantucket Sound, there are numerous shoals of shifting sand. These form a sort of broad belt, which curves eastward. Fear has arisen that the flying beaches of Monomoy and Great Point might be built up by the sea on the crest of these shoals in such manner as to close the entrance to Nantucket Sound. This change, which would be fraught with embarrassment to the coastwise navigation, seems now, so long as land and sea remain stable, not likely to take place, because the shoals lie well eastward and seaward of the flying beaches, which are not only inclined inward, toward the axis of the sound, but are moving in that direction. This inward movement of the flying beach is clearly shown by the changes at Monomoy, but is less obvious from the charts and surveys of Great Point, on Nantucket. Nevertheless, as the headland on the east side of Nantucket recedes with the attack of the sea, so must the flying beach attached to it recede with the recession of the shore. Handkerchief Shoal, off the southwest end of Monomoy, actually extends the flying beach about one-third of the space between the southern point of Monomoy bar and Great Point. This shoal has grown southward since accurate surveys of it were first made. On the other hand, Great Point, the end of the flying beach from Nantucket, has been nearly stationary, and its underwater extension turns abruptly northeastward. In fact, the end of the bar has receded several hundred feet during the last century, whereas Monomoy has been built out as much as two miles. Thus, while the space between the points is becoming narrower the Monomoy beach is working southwestward and forcing the current southward against Great Point, and this process will apparently continue for a long time, because more sand is available for transportation from the shore of Cape Cod than from Nantucket. Furthermore, the coast of Cape Cod, unlike that of Nantucket, is not defended by off-shore banks and shoals.

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[1] Ann. Rept. [Massachusetts] Harbor and Land Commissioners for the year 1886, pp. 37–46; with map. Boston, 1887.

WEBB'S ISLAND

Local histories repeat an account of the disappearance of "Webb's Island," which once lay *southeast* of Chatham or of Stage Harbor, and hence outside of the existing Chatham or Monomoy bar, in such manner as to have been exposed to the attack of the sea. The earliest account of the disappearance of this island is given by a writer[1] in the Massachusetts Magazine for December, 1790, who says:

> When the English first settled upon the Cape, there was an island off Chatham, three leagues distant, called Webb's Island, containing twenty acres, covered with red cedar or savin. The inhabitants of Nantucket used to carry wood from it. This island has been wholly washed away for almost a century. A large rock that was upon the island and which settled as the earth washed away, now marks the place; it rises as much above the bottom of the sea as it used to rise above the surface of the ground. The water is six feet deep on this spot.

The article quoted fails to give the direction in which the island lay from Chatham. As the island seems to have disappeared about 1700 it ought to appear on charts published before that year and to be missing from those published later. Henri de Champlain shows no such island on his chart of the coast drawn in 1606, nor does Captain John Smith or later navigators, though most if not all of them had troublesome experiences with the shoals off Monomoy beach. There is thus no seaman's record of a lost island lying southeast of Chatham from 1606 onward.

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[1] Quoted by William C. Smith in A history of Chatham Hyannis, 1909, Part I, p. 11, footnote 25. Smith supplies the direction "southeast from Stage Harbor" in his account, stating that the existence of the island is established by unanimous local tradition.

In his cautious remarks upon the ''lost island'' Mitchell notes that a map of Nantucket Sound and Nantucket Shoals in The English Coast Pilot of 1707 shows a ''Webb's Island'' as a part of the sand flat in Monomoy Beach, southwest of Chatham Harbor. The Southack (?) chart, which bears an inscription noting the crossing of the Cape at Orleans by a whale boat in 1717 and which is probably the same chart as that of 1707, also shows Webb's Island. This name was well established in Chatham for a part of the Monomoy bar as it existed in 1738, half a century before the legend started in the Massachusetts Magazine, as shown by a record reproduced by Smith[1] from the files of the Superior Court of Judicature describing lands on Monomoy Great Beach, in which it appears that there is a reference to the ''marsh which lies to the northward of a place called Webb's Island.'' It would appear that Webb's Island was an integral part of the shifting winged beach of Monomoy. There seems no good reason to believe that ''Webb Island'' lay outside of the beach.

Mitchell notes that on the Atlantic Coast Pilot chart of 1707, and the Southack (?) chart in use in 1717, there is inscribed off the south end of Webb's Island the words, ''the Seal Island sunken channel way,'' presumably a reference to land that disappeared before 1707.

THE PROVINCELANDS HOOK

At the north end of Cape Cod peninsula there is a historic sand hook known as the Provincelands, the title to which is held by the Commonwealth.[2] Several detailed maps of Provincetown harbor and the surrounding dunes and bars or barrier beaches have been made from time to time, because the harbor is a port of refuge and a fishing station. The most elaborate study of the origin and mode of development of the hook is that made by W. M. Davis[3] in 1896. It constitutes the northern complement of Monomoy flying beach, the wing-bar of Gulliver's winged beheadland of Cape Cod. Davis called attention to the fact that before this wing-bar or sandy hook was formed, the sea played freely around the end of the glacial part of the Cape, forming the headland known as Pilgrim Heights, or High Head, in North Truro.

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[1] Smith, W. C., A history of Chatham, Mass., Part II, p. 208, footnote 27, Hyannis, 1913.

[2] For the history of the control of these lands by the State and the attempts to regulate the work of the winds in blowing the sand, see Second Ann. Rept. of the Trustees of Public Reservations, for 1892, Appendix III, House No. 339, pp. 65 et seq., Boston, 1893. The original State document contains a map of the dunes drawn with a 5-foot contour interval.

[3] Davis, W. M., The outline of Cape Cod, Proc. Am. Sci., **31**, pp. 303–332, 1896. Also reprinted in Geog. Essays, edited by D. W. Johnson, Chap. 25, pp. 690–724, Boston, 1909.

High Head, or Pilgrim Heights, is cliffed in three directions, none of which coincides with the present trends of long-shore marine action. On the north side of the head there is an old, somewhat dissected cliff which is about 2 miles long and is separated by the ''Salt Meadow'' from the dune-crested beach that joins the Provincelands on the ocean side to the end of the Cape near Highland Light Coast Guard Station. This cliff is regarded by Davis as a remnant of an early, outer coast line of the headland of Cape Cod, a line that existed about 1,200 years ago. As the coast of the ocean or ''back'' side of the Cape retreated under the action of the sea and straightened out, the flying beach would spring off from the head of the Cape near B and the sandy hook beyond the point of contact with the coast would grow outward. Thus the oldest part of the hook at Provincetown is on the inside next the harbor and the newer part on the north.

The cliff on the west side of High Head is older and is apparently contemporaneous with that on the north, behind the Salt Meadow, cut before the flying beach and hook at Provincetown began to form, and a newer one farther south which, as it lies farther east, has sent off a flying beach from the head enclosing Pilgrim Lake, or East Harbor, as the lagoon was called before this beach united with the main beach.

In 1916 Vaughan observed on the outer beach, near Woods End, at low tide, a small area of angular gravel of glacial origin that seems to be abnormal for the hooked spit there, which appears to rest upon an older deposit. This gravel must have formed a shoal before the Woods End spit was built out to its present outline. As the cliffs at Pilgrim Heights indicate an open sea when they were cut, the time of the removal by wave action of glacial deposits there that lay above sea level was probably the time the shoal was formed. The shoal and any island or land that lay in that position would have given direction and support to the sand-spit that now forms the outer barrier of the harbor. The gravel recalls the Jameco (?) material underlying the Gardiners (?) clay at Highland light, and this material extended over the site of Provincetown harbor before the land was cut away to form the cliffs at Pilgrim Heights.

The Provincetown wing-bar has undergone little change since it was first mapped. In 1857 Whiting found by comparing late maps with those made by the survey of 1849, that the changes were most pronounced near Race Point and East Harbor. Lance's Harbor had been closed, and the enclosing beach for 2½ to 3 miles between Race Point and Long Point, forming the western finger of the Cape, had been driven in from 100 to 300 feet. In 1849 the beach between East Harbor and the ocean was about 300 feet wide where narrowest and about 40 feet high.[1] In 1857 Mitchell found the beach at this place about 100 feet wide and 12 to 15 feet high. He records a report that the sea had broken over this place in the preceding winter.

Certain small-scale maps that form illustrations in books published at the end of the eighteenth century[2] show a passage through the outer beach at the west end of East Harbor (Pilgrim Lake on recent charts), seeming to indicate that for a time after the survey by Des Barres the sea broke through the bar at this place; but no authentic record of such an occurrence has been found. Any such irruption, however disastrous it might have been to Provincetown Harbor, would have soon been closed by the long-shore transportation of sand from the cliffs of Truro and Wellfleet.

In 1868–69 a dike was built at the "wading place" at High Head (or Pilgrim Heights) by the United States, and another dike was built to close the connection between East Harbor and the bay, thus converting the East Harbor into Pilgrim Lake. In 1870 a dike was built at the head of Lancy's Harbor, at the foot of Abel Hill, to prevent the flow of the tide from Lancy's Harbor into Provincetown Harbor. More recently a dike has been built from Steven's Point across the House Point Island flats to Long Point. Formerly there was a small islet on these flats, known as House Point Island, which has gradually disappeared. In 1890 Marindin found Lancy's Harbor a "dry sand and gravel slough."

In the Coast Survey Report of 1867, Whiting[3] states that, between Graham's survey in 1835 and his re-survey in 1867, Long Point had become extended above high water as much as 2,460 feet. The flats between Long Point and the western part of the village advanced in the same period (32 years) an average distance of 275 feet upon the harbor. Beach Point, which was built out from the west side of High Head, advanced in the same period 1,000 feet on the south side of East Harbor, but the main shore of the inlet opposite the point had receded 200 feet. At the same time the bar had moved inward about 200 feet. On the ocean side of the harbor Whiting found the bar still more reduced in width and height than it was in Mitchell's survey, and he recommended that the East Harbor be closed.

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[1] In addition to the general charts of Cape Cod already listed, there is a chart of Cape Cod Harbor by J. D. Graham, U. S. Topographical Engineer, 1836, accompanying Document 121, 25th Congress, 2nd session, surveyed 1833–35, scale 1/10,560. The harbor was surveyed by the U. S. Coast Survey in 1849, and re-surveyed by H. L. Whiting in 1857, see U. S. Coast Survey Report for 1857, pp. 148–149, plate No. 9, map of Provincetown Harbor. Whiting made another survey of the harbor in 1867. Again the harbor was surveyed by Henry L. Marindin in 1890, see U. S. Coast and Geodetic Survey for 1891, Part 2, Appendix No. 8, pp. 283–288, plates Nos. 11, 12.

[2] The State of Massachusetts from the best information, 1799, Engraved for New Encyclopedia. Published by I. Low, New York, Scale, 20 miles to one inch. A map of Massachusetts, from the best authorities, by J. Denison, published by Thomas & Andrews, Boston. No date. Scale 1/564,960.

[3] U. S. Coast Survey Report for 1867, pp. 151–156.

In 1890 Marindin found that the outer beach back of East Harbor had come in still farther since the survey of 1867, so that the width of the barrier there had been reduced; also that although the harbor opposite the town showed scouring and deepening, the mud flats between Stevens Point and Long Point had advanced somewhat into the harbor.

The surveys of Monomoy and Provincetown harbor showed that much more material is being transported southward along the Cape to the sand bars of Chatham and Monomoy than northward to Provincetown because of the greater force of the northeast storms. Moreover, Cape Cod is fended on the southeast by great shoals from the full force of the waves. During a northeaster the Provincetown spit is driven in from the ocean side, hence the bar that ends in Long Point. Only a small part of the sand and gravel taken from the high cliffs of Truro and Wellfleet appear to lodge above sea level on the Provincetown bar, and Nauset Beach and Monomoy probably draw supplies from the shore north of the middle of the coastline, between the ends of these bars. The low plain of Eastham becomes thinner toward the west, as does to some extent the high plain of Wellfleet, which also decreases in thickness westward owing to the widening and deepening of the hollows in that direction, and the consequence is a reduction in the quantity of gravel and sand that is fed to the longshore current on the ocean side. Marindin shows that the rate of retreat of the coast is most rapid along the Truro plain — about 8 feet a year as compared with 5 feet a year along the Eastham plain — so that a large part of the material handled by the waves and currents comes from the erosion of the high cliffs of Wellfleet and Truro. This more rapid retreat on the north turns the curving coast farther to the west of north and diminishes the southward component of longshore shift of material during northeast gales. The drift of sand toward the Provincetown bar being thus increased, if it should counterbalance the loss from the decrease in thickness of the deposits above sea level as the coast recedes, would tend to establish stability and to preserve Provincetown harbor, at least in outline.

On the inside of the arm of the Cape there are a number of islands and offshore bars that end on the south in Billingsgate Island. On Des Barres' chart (1780) no barrier beach is shown between the land at South Truro and

Bound Brook Island nor between Griffin Island and Great Island and Great Island and Great Beach Hill Island, such as is shown on the chart of 1887. It is said that the barrier beach once continued southward to Billingsgate Island and beyond it to the little remnant hook island farther south, on which Billingsgate lighthouse stood in the 70's, when a remnant of this barrier beach formed a small island between Beach Hill Island and Billingsgate Island. In recent years much of the northern part of Billingsgate Island has been washed away.

BARNSTABLE BEACH

Barnstable Harbor, on the south shore of Cape Cod Bay, is guarded on the north by a long barrier beach that is built eastward along the curving shore where the sea beats against drift hills back of the frontal moraine, such as Scorton Neck, to which the beach is an appendage.

A detailed chart of Barnstable harbor, on a scale of 1 to 20,000 was prepared in 1861 by Henry Mitchell and published in the U. S. Coast Survey Report for that year. (See page 34, chart No. 5.) The beach known as ''Sandy Neck'' has undergone few changes since this survey was made. It is said that since the breakwater at the entrance to the Cape Cod Canal was built the beach along this shore has begun to wash away. If this statement is true the change has probably occurred because the longshore drift from the high cliffs on the west side of the Bay no longer reaches the barrier beaches east of the canal and must therefore be deposited near the breakwaters of the canal.

THE SOUTH SHORE OF THE CAPE

The south shore of the Cape is lined by barrier beaches that face the relatively quiet water of Nantucket and Vineyard sounds. Some of these barrier beaches form small winged beheadlands, such as that on the Neck near Osterville, and on Powers Neck. A curved bar and beach forms the shore of New Harbor near Centreville. Beach cusps may be seen at Cotuit Highlands, at the entrance to Osterville Harbor, at Hyannis Point, in the beach barrier to Great Pond, in Falmouth and Waquoit Bay.

LAND-TIED ISLANDS

Certain small peninsulas appear to be land-tied islands, particularly those on the Buzzards Bay shore, such as Wenaumet Neck, Scraggy Neck, Bennet's Neck, Chappaquoit Point, Long Neck, Great Island (Point Gammon) off Yarmouth, Morris Island (near Chatham), Indian Neck (near Wellfleet), and the so-called islands between South Truro and Great Beach Hill Island.

Not every body of land that is formed of glacial drift and is tied to a larger land mass has been an island since the glaciers disappeared. When the land stood higher in relation to the sea, the depressions between the elevations that now form most of the islands in the Cape Cod district were simply low places in the land. As the sea rose it would reach the level of one of the depressions and flood it with sea water, making an island out of the detached fragment of land. If, however, the beach action were sufficiently strong a barrier beach might be thrown across the depression as fast as it became lowered below the level of the sea, and thus the beach-tied island may have existed as an island except for some temporary irruption of the sea over the beach barrier.

The arm of Cape Cod from Town Cove northward consists at present of two islands tied together by a bar at the head of Pamet River. The southern or Eastham member of this insular group is separated from the mainland by the old boat channel from Boat Meadow River through Jeremiah's ditch to Town Cove. A dike that has a gateway just west of the railroad track about a mile north of the Orleans railway station prevents the sea from flowing through this ancient channel, most of which is filled with marsh vegetation.

The old glacial drift at the head of Pamet River has been cut away and the sea has been brought into contact with a depression, just as it has at Blackfish Creek, in South Wellfleet, where the coast is now about three-fourths of a mile from the head of a depression. Without any change in the level of land and sea, the coast will after a time have receded so far as to admit the ocean to the east end of the creek unless a bar is thrown across the entrance. Blackfish Creek probably represents an early stage of the Pamet River depression before the sea had cut back the coast so far as to tap the valley.

If we plot the direction of the longshore drift against the chief tangent bars and winged beaches of the Cape and Bay inside it (see fig. 23) it will become obvious that wash from the shores of the Bay become pocketed except where tidal scour carries them out upon the bottom, and that the headland of the Cape is being driven inward by a general southward movement of the coastal waste.

Work of the Wind on Cape Cod

The geological action of the wind on Cape Cod consists of the deflation of the glacial gravel of the upland, the erosion of the cliffs, and the formation of dunes along the beaches.

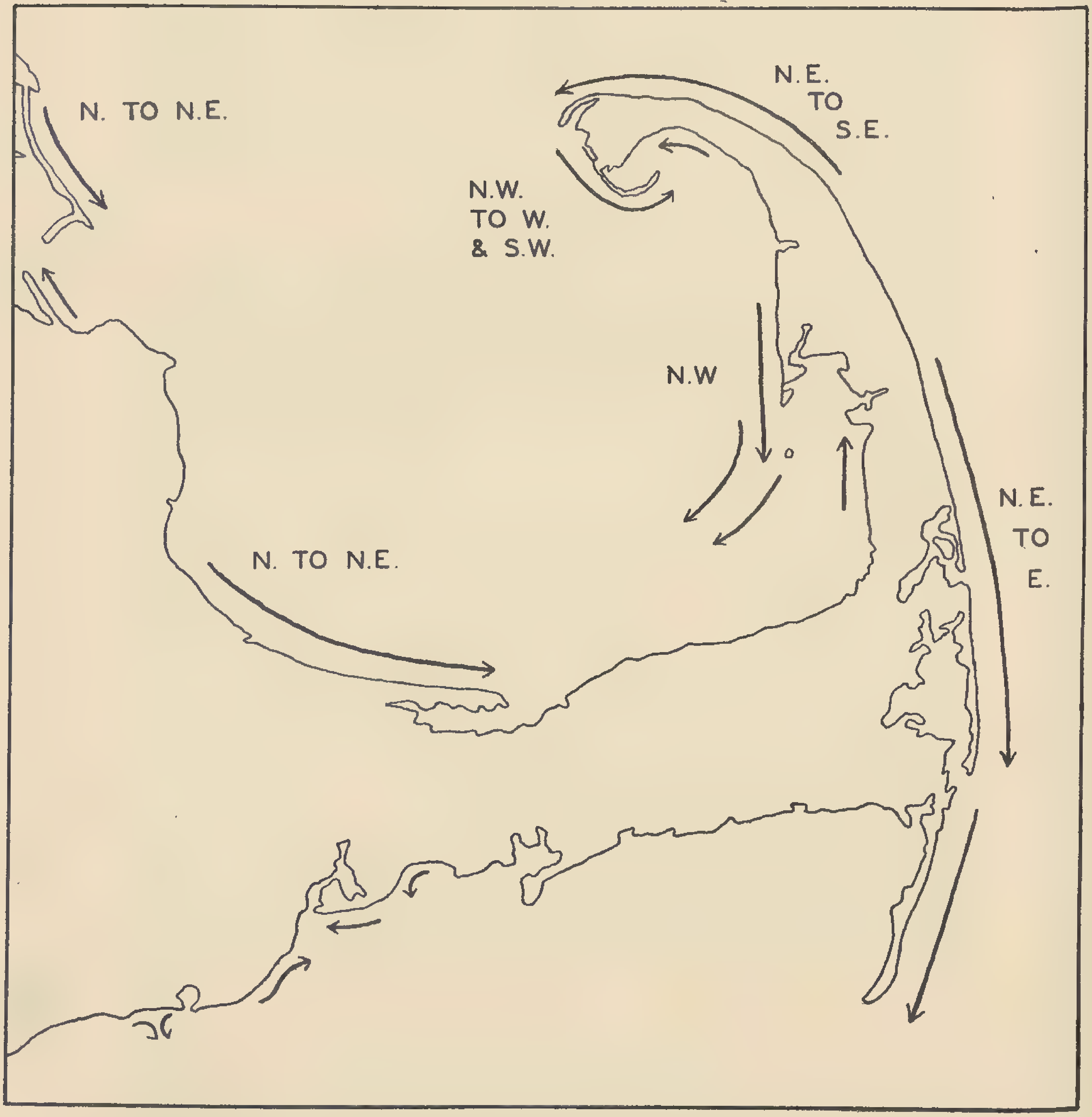

Fig. 23.—Outline map of Cape Cod and Cape Cod Bay showing longshore drift, as indicated by the chief beaches and sandbars.

THE DEFLATION OF THE GLACIAL GRAVEL

At many places on the Cape, particularly near the brows of the cliffs, the wind has swept away the soil and is moving the glacial sand across tracts of lag gravel. The pebbles and the angular rock fragments in such tracts thus become highly polished and carved. The "blowholes" or lag-gravel tracts and the windswept face of the cliff at Highland Light afford an excellent field for observing the action of wind on glacial material. Some of the effects of this action have been described by Davis,[1] who found that sand-blasted pebbles or glyptoliths are widely distributed on the Cape in places where the stratified glacial gravel is exposed to the action of the wind. He also described numerous glyptoliths that were buried, with the carved side up, in the superficial part of the glacial gravel. He writes:[2]

> The highest cliff of stratified sands and gravels on the southern shore is at Succonnesset Point, between Falmouth and Cotuit. The bluff here rises twenty or thirty feet above sea-level. The occasional pebbles scattered through the greater part of this section were not facetted, but in the upper eight or ten feet, where pebbles were common, many carved pebbles were found, and, as before, they lay with the facetted side uppermost. The greatest depth at which a pebble with distinct facets was found was about nine feet beneath the surface. Many carved pebbles were found along the base of the cliff, sometimes, apparently, in place, but then held in large masses of gravel which had slipped down from the top of the cliff.
>
> If it be postulated that these buried facetted pebbles have been carved by wind-blown sand, as they certainly seem to be, then it must be concluded that at least those beds of stratified sands and gravels which contain facetted pebbles were deposited by subaerial processes, and not by marine processes below sea level.

In addition to the more or less symmetrical carved pebbles bearing facets whose intersection produces edges there are pebbles in which grooves and pits have been worn by the sand blast. These sand-blasted pebbles are found in situations which indicate that they were shaped at many times since the glacial period, or at all times, for they are obviously now being shaped.

The following data concerning the direction of the wind at Provincetown, obtained by Dr. T. W. Vaughan from the United States Weather Bureau, may be serviceable in an investigation of the dunes and sand-blasted pebbles at the upper end of Cape Cod.

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[1] Davis, W. M., Facetted pebbles on Cape Cod, Mass., Proc., Boston Soc. Nat. Hist. **26**, pp. 166–175, pls. 2, 1894.

[2] *Op. cit.*, pp. 168–169.

Number of times the wind was observed blowing from different points of the compass at Provincetown in **1882**, **1883** *and* **1884**. *Computed from three daily observations made at* **7** *am.,* **3** *p. m., and* **11** *p. m.*

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
						1882						
N..........			11	5	11	2	5	4	3	17	21	8
N. E........			12	12	19	3	6	12	30	12	15	5
E...........			3	3	3	3	1	1	3	13	1	3
S. E........			9	15	9	7	7	8	16	11	0	5
S...........			13	10	9	15	18	25	12	7	7	3
S. W........			9	18	27	31	36	29	9	16	6	14
W..........			7	3	3	12	11	9	6	6	12	25
N. W.......			29	24	12	18	7	5	11	10	24	25
						1883						
N..........	9	6	11	13	7	2	7	9	10	22	10	10
N. E........	10	3	4	13	6	3	8	13	17	15	4	12
E...........	8	1	3	9	10	7	4	12	10	10	4	4
S. E........	9	11	4	7	15	9	4	4	7	8	2	5
S...........	5	6	9	13	11	25	25	3	9	9	13	11
S. W........	13	17	13	15	27	27	22	27	15	8	25	12
W.........	15	26	13	6	5	13	12	13	11	6	12	14
N. W.......	22	14	33	14	10	4	11	9	7	9	19	23
						1884						
N..........	15	4	8									
N. E........	5	12	10									
E..........	5	7	5									
S. E........	7	16	9									
S..........	7	7	10									
S. W........	17	15	12									
W..........	17	7	12									
N. W.......	17	17	27									

Average velocity, in miles per hour, of wind blowing from specified directions at Provincetown, Mass.

1882

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
N..........			13	14	13	4	6	9	19	11	12	12
N. E........			15	15	13	13	7	4	12	8	13	6
E...........			9	4	10	4	5	2	6	5	10	11
S. E........			14	11	8	8	9	6	12	10	10	16
S...........			15	13	10	10	8	9	10	7	12	10
S. W........			8	9	10	9	8	8	6	8	7	11
W..........			9	10	8	6	6	4	7	6	10	11
N. W.......			14	11	9	10	7	8	10	12	12	13

1883

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*Jxne*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
N..........	14	12	14	10	10	8	9	6	8	14	13	14
N. E........	11	8	10	10	8	7	7	10	6	9	9	10
E...........	10	1	12	8	9	6	3	7	5	6	12	11
S. E........	12	12	14	7	9	10	4	8	6	10	23	16
S...........	18	8	15	12	14	10	8	8	9	11	9	10
S. W........	12	9	12	9	10	9	11	8	8	9	10	11
W..........	13	11	11	5	6	6	4	6	6	9	9	11
N. W.......	12	15	16	10	10	6	9	9	13	10	14	15

1884

N..........	11	10	10
N. E........	10	11	11
E...........	11	6	8
S. E........	20	12	15
S...........	12	7	9
S. W........	13	12	9
W..........	11	12	10
N. W.......	12	15	13

The prevailing wind blows from the southwest, and as it is fairly dry it probably does most of the cutting. The winds from the north, northeast, east, southeast, and south are usually damp, and the moisture they form causes the grains of sand to resist them so that only a strong wind from these quarters can move the sand.

The sand and dust blown from the lag-gravel tracts of the glacial drift form conspicuous deposits only near the edges of cliffs, where the work of the wind is reënforced by the vertical movements there set up. High dunes are formed in such positions, and nowhere more abundantly in this region than in the stretch on the outside of Cape Cod between Highland Light and Nauset Light, just where the cliffs are highest and steepest. A belt of such dunes and associated tracts of lag-gravel border the top of the cliff in Wellfleet and Truro for a considerable distance north and south of the Pamet River coast guard station at elevations as high as 100 feet above sea level where the older glacial gravel attains this level.

EROSION OF CLIFFS BY WINDS

The wind loosens and tears down the incoherent gravel and sand in the coastal bluffs. On fair days when dry winds are blowing in a favorable direction, pebbles loosened by the blowing out of the sand at their bases roll down to a sandy talus. Many of these pebbles take somewhat curved courses, ricochetting so as to leave a series of pits on the beach sand leading to the resting place of the spent pebble. Hundreds of small streams of dry sand run out from incoherent layers to add their contribution to the growing fan of talus that rises between the beach and the top of the wasting cliff. When very high winds are blowing inland, sand and dust are carried up the slope and on to the surface back of the cliff. These æolian deposits at the tops of cliffs form mainly in the prism of slack air motion that lies just back of the edge of the cliff, where vertical movement is at times favorable to deposition. With the secular falling away of the top of the cliff, the horizontally stratified dune sand loses its fore part in the same process and becomes a distinct deposit, a few feet thick, at the top of the cliff. Such a deposit is generally separated from the old glacial surface by a layer of lag-gravel with or without sand-carved pebbles, by a layer of soil, or, more rarely, by a thin bed of shell made by the aboriginal inhabitants.

DUNES FORMED FROM BEACHES

The dunes on the beaches differ from the deposits of wind-blown sand because their component sand is sorted by waves. Fine dust, such as is deposited by the wind that blows over the unmodified glacial deposits, is not found in the beach dunes because the finer particles of the dunes have been swept into the sea by the undertow. Furthermore, most of the small particles of the softer minerals in the wind-laid deposits derived directly from the glacial drift are ground down between the pebbles in the mill of the surf and carried seaward with the clay. Along the beach, as in the bared tracts in the interior, there are two contrasted land surfaces — the beach whence the sand is blown (Plate 35, fig. 1) and the dune tract to which the sand is carried by the wind. The beach is in a certain sense a lag-gravel tract in places where scattered pebbles occur near headlands or in front of cliffs from which pebbles are supplied to the beach, but owing to the regular return of the tide and the greater power of the waves to shape and distribute pebbles and sand on the beach, the work of the wind on the beach is limited to shifting the sand and, under favorable circumstances, to producing a paradoxical movement of pebbles in a direction opposite to that of the wind. The sand-blasted glyptoliths found in the glacial upland lag-gravel tracts are not found on the beach, where the frequent inversion of pebbles and the change in the setting of the surface give no time for sand blasting.

The principal dunes of the Cape Cod peninsula are formed by the inshore wind on the great flying beaches at the north and south ends of the headland —

that is, at Provincetown and Monomoy, and along the Barnstable beach. Many other small dunes are found on the shore of the open sea, along the sound on the south, and along the shore of the bay, where the beaches furnish the sand. The dunes of Provincetown are the best known in this part of the coast.

DUNES OF THE PROVINCELANDS

The dunes of the Provincelands are the highest along the southeastern coast of New England. They form three distinct belts or tracts, each showing some peculiarity of form and arrangement. The outermost belt skirts the beach from Race Point to the place where the Provincetown sand hook is attached to the glacial headland between High Head and the Highland Lighthouse. This region is of recent origin. Here the beach and the dunes are partly separated from the main tract by the slough known as Race Run, a slight depression that runs nearly continuously through the district. The Peaked Hills, which stand between 2 and 2½ miles from Race Point Lighthouse, were the chief accumulations of wind-blown sand in this belt in 1835 (Plate **35**, fig. 2). On Graham's chart, which is based on surveys made in 1833–35, the highest points in these dunes are given as 44 and 46 feet. Farther east individual dunes reached elevations of 49, 52.5 and 54 feet, the last one lying just east of the boundary line between Provincetown and Truro. East of High Head, near the junction of the sand hook with the mainland of the Cape, there is a group of old wooded dunes, one of which is known as "the island." These dunes are probably a part of an older deposit than that at Peaked Hills, having been formed when the beach joined the mainland at a point east of its present position. These outer dunes are now considerably reduced.

On the south side of the Race Run slough there is a second belt of more stately dunes, which form a nearly continuous ridge that extends from the northwest side of East Harbor, or Pilgrim Lake, to a point within about a mile of the west coast. On Graham's chart the highest dune indicated in Provincetown had an elevation of 64 feet, and one in Truro, near the west end of Pilgrim Lake had an elevation of 85 feet. Much of the surface of this dune, as shown on the chart, was covered and anchored by transplanted beach grass. (Plate **36**, fig. 1). The survey of 1887 shows that this ridge of dunes had increased in elevation near its east and west ends, two points near the west end and three near the east end, rising above 80 feet.

According to a survey made by McClintock in 1892 the great ridge had risen above the height shown by Graham's survey, at one point attaining an elevation of 100 feet, which appears to be the greatest height reached by any dune in the district. By comparing the present position of the dune ridge with its position as shown on Graham's chart McClintock[1] concluded that the ridge had steadily moved inward from the ocean toward the harbor at a rate of about 10 feet a year. ''The north wind,'' he writes, ''as a motive power annually carries more than one million tons of sand a distance of half a mile from the northern front to the rear of the ridge.'' In the same report Mr. Heman S. Cook, a native resident, testified that sand is blown in by the north wind but by no other. The result of this general southerly movement of the dune is to bare the surface that was once covered by the sand on the north side, revealing one or two sets of buried soils containing stumps of trees, and to bury the living forest on the south side. On its east side the ridge has thus partly merged into the outlying dunes known as Mounts Ararat and Gilboa on Graham's chart, though these dunes still retain their general forms and altitudes. Intermediate points, however, have been much altered by the blowing away of the sand, which is driven southeastward by strong northwest dry winds.

South of the main line of dunes north of Great Pond stands Negro Head, the northeast arm of a horseshoe-shaped dune that is open to the northwest, as shown on Graham's map of 1835. At that time Negro Head had an elevation of 88 feet. This dune has been much altered in form and somewhat reduced in altitude. Farther east, a ridge of dunes that skirts the northern margin of ponds or sloughs stretches toward Pilgrim Lake. This ridge includes Mounts Gilboa and Ararat of Graham's chart, which had elevations of 106 and 100 feet, respectively, in 1835, whereas, according to the survey of 1887, Town Hill, the site of the Pilgrim Monument, was the only dune on the hook having an elevation of 100 feet.

The dunes between the ponds and Race Run form three well defined belts, which taper out westward. One of these belts borders Race Run, and the Snake Hills of Graham's chart form the oldest one of three. The depressions between these ridges are of the same origin as Race Run, the unfilled space behind successively offset bars growing westward parallel to the shore.

Between these outer dune ridges and the shore of the harbor the wind, in forming and reforming dunes, has produced a topography that masks the original alignment of the dunes along the earliest bars and beaches.

There are three of these groups of dunes, which present rather steep fronts to the harbor. One group rises back of Clapp's Pond and extends eastward between Duck and Bennett's ponds (See Plate **36**, fig. 2), and thence eastward into the knot of dunes that culminates in Mounts Gilboa and Ararat, names which appear on Graham's chart. South of this line, between Shank Painter and Clapp's ponds, there is a well defined but shorter belt of dunes, and this belt terminates eastward in the high dune known as Town Hill, which forms the pedestal of the Pilgrim memorial monument.[1] South of Shank Painter Pond there is an inosculating belt of dunes, which encloses depressions, becomes narrower toward the east and merges into the base of Town Hill. The southern steep faces of these dunes are in places the sites of recently moved sand. The dunes advance their bases into swamps and bury the vegetation.

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[1] McClintock, John N., Report of the Trustees of Public Reservations on the subject of the Province Lands, Feb., 1893, Mass. House . . . No. 339, pp. 16–17, with accompanying map of the Province Lands.

Although the fronts of these three groups appear to be aligned in a general view, the alignment is difficult to perceive at close range. The southernmost group, which faces the shore of the harbor, is evidently a product of the forces that formed the coast line in that region. The inner line of dunes, although it shows local sinuosities, is so nearly in alignment with the main ridge on the north that, despite the erosion and the alteration of their forms by the deposition of sand on their lee slopes, the dunes are of similar origin. The low tracts between them would therefore correspond to Race Run and the slough between the present beach and the main ridge of dunes. Although this view is consonant with the theory of the formation of the bars or barrier beaches at the broad west end of the hook, little structural evidence is available to support that theory. Back of each of the irregular lines of dunes there is a much eroded surface of remnants of dunes, which are anchored by vegetation and which show that the dunes as a whole have moved inward toward the harbor and that their positions and forms were once very different. These lines of dunes correspond to old beach lines, on the landward or lee side of which they may have been deposited; but the southernmost dunes, near the harbor, are older than those next north, and so on through the successive belts toward the north.

The mass of the dunes south of the principal ridge consists, not of delicately balanced heaps of sand with crescentic basal outlines convex to the wind but of a medley of forms, partly of constructive, partly of destructive origin. This irregularity of form is caused chiefly by shrubs, trees, and beach grass, which anchor the sand and interfere with the free sweep of air currents. These complex conditions in the zone back of the growing front of the lines of dunes, where erosion prevails over deposition, have caused a variety of dune forms. Certain lines of old accumulations remain, not without signs of rebuilding, and form minor northwestward-bending scraggly ridges between wind-swept basins. The type of topography is very clearly shown on Graham's chart of 1835.

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[1] This monument was erected by the Cape Cod Pilgrim Memorial Association. The corner stone was laid August 20, 1907, and the structure was dedicated August 5, 1910. The monument, which is made of Maine granite and is in the Italian Renaissance style, was copied from the Torre del Mangia, in Siena, Italy. It is 252 feet 7½ inches high, and its top stands about 352 feet above sea level.

At the time of the European settlement of the Provincelands the older dune tract back of the town and south of the main dune ridge appears to have been well anchored by the growth of scrub trees peculiar to the district; but the thoughtless robbery of the dunes of their vegetal cover, despite legislative measures designed to prevent it, early in the history of the Massachusetts colony gave the winds a free chance to start the sand moving toward the harbor. In the second and third decades of the nineteenth century beach grass was planted to arrest the action of the winds. The history of this work is given in a report of the Trustees of Public Reservations on the subject of the Province Lands for 1893.

THE DUNES OF BARNSTABLE

The flying beach terminating in Sandy Neck, between Barnstable harbor and the south shore of Cape Cod Bay, is the site of a narrow strip of low dunes. Along its southern somewhat crenulate border this strip shows traces of old stages in the forward building of the hooked end of the eastward-growing spit. Here six or more of these old hooks, now bearing dunes, are indistinctly shown. The latest line of dunes, back of the Sandy Neck light, is separated from the older accumulations on the harbor side by a cove and a strip of marsh.[1] Certain minor details in the distribution of small dunes at places along the harbor side of Sandy Neck — as, for instance, back of Mussel Point and near the head of Wells Creek — indicate the submergence of dunes since their formation, for the dunes are now surrounded or are confronted at their bases by salt marsh. However, as this condition appears to be connected with the history of Mussel Point and with the development of the harbor when it was not only shorter than it now is but was narrower at its entrance, it seems likely that these dunes were formed when the water in the harbor did not rise as high as it does now.

THE DUNES OF MONOMOY

Monomoy, which is now covered with dunes, has been alternately an island and a peninsula, its form depending on changes in the position of the barrier beach near Chatham. The most characteristic features of this changeful tract are the development of a long, narrow line of dunes parallel to its eastern shore and the accumulation of less continuous and regular forms about Powder Hole, at the southern growing end of the sand hook.[1]

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[1] For a map of this tract, see Coast Survey chart No. 339, Barnstable Harbor, scale 1/20,000, May, 1914.

Nauset and other beaches are surmounted by small, low dunes. Some of those on the ocean side exhibit breaches made by the wind and the sea at times of great storms. These dunes, like the beaches from whose sand they are fed, move inward with the shifting of the barrier beach upon the marsh and the glacial drift except where a steep coast prevents their accumulation back of the actual beach. An on shore wind is likely to form dunes when the sun is shining and the surface sand is dry and incoherent, but the dry off shore wind reduces the accumulations by transferring the sand to the beach for redistribution by the surf and currents.

Swamps and Marshes

The recent vegetal deposits on Cape Cod cover small tracts of freshwater swamps and larger areas of marine marshes.

FRESHWATER SWAMPS

Before cranberries were grown on Cape Cod many small depressions there were swamps. Other similar depressions, whose sandy floors stand above the water-plane of the vicinity, have also been converted into cranberry bogs. It is therefore now difficult to determine whether many of the cranberry bogs occupy the sites of natural swamps.[2]

Small strips of swamp are found at many places around the shores of the numerous lakelets on the Cape or in depressions in the glacial drift that are too shallow to form the sites of lakes. The largest swamps are in the towns of Dennis and Harwich, on the southern border of the Cape, where depressions in the glacial drift are occupied by swamp-making vegetation. The swamp bordering Swan Pond River, in the southern part of Dennis, covers about one square mile. East of it, in Harwich, the total area of mappable swamp land is about five square miles. Many smaller swamps lie in the bottoms of kettle holes and ice-block depressions in the adjoining sand plains.

Most of the swamps on the Cape may also be regarded as peat bogs. When the first geological survey of the Commonwealth was made, peat was in local use and was dug from bogs in Yarmouth, Brewster, Orleans, Eastham, Wellfleet and Truro.[1]

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[1] Coast Survey chart No. 250. The eastern entrance to Nantucket Sound, May, 1913, exhibits the general character of these deposits.

[2] For a popular and instructive account of the vegetation growing in ponds on Cape Cod and of the transformation of ponds into swamps, see William Gould Vinal, Cape Cod Ponds, Cape Cod Magazine, **3**, pp. 9–14, Sept. 1917.

Many of the ice-block holes that are occupied by water have not become swamps because of the depth of the water in them. The swamp that lies east of the north end of John Pond, in Mashpee, and possibly the swamp in the upper course of Green Pond rivulet above the village of East Falmouth, appear to have been originally shallow lakes. The small oval swamp in the Falmouth moraine southeast of North Pocasset was probably a lakelet like the neighboring Flax Pond.

Some sections of the beds along the coast reveal bogs containing peat and buried logs, as well as stumps of trees. Many of these bogs were formed in ice-block holes in the glacial drift, the seaward sides of which have been removed by the encroachment of the sea. The vegetal accumulations in such a bog were exposed in 1915 and 1916 on the beach under the Nauset Coast Guard Station, in Eastham. The section of this ancient swamp, which was about 4 feet thick, showed two levels of stumps and fallen logs. The logs were the trunks of trees larger than any now growing in that part of the Cape and show that the swamp was formed at a considerable distance from the sea coast.

CHAMAECYPARIS BOG NEAR WOODS HOLE

The most instructive of these ancient swamps is that described by Mr. H. H. Bartlett[2] as a submarine Chamaecyparis bog at Woods Hole. This bog is on the east side of a small cove that forms the southwest arm of Quamquisset harbor, about a mile north of Woods Hole wharf.

In describing this bog Mr. Bartlett writes:[3]

> Its greatest width is about four hundred and fifty feet; its length perhaps twelve hundred feet. Seven hundred feet inland there is a constriction where the width is only about forty feet. So far as the vegetation is concerned, the seaward portion is a typical salt meadow. Otherwise, however, it presents two anomalous features, in that it is neither penetrated by a tidal creek nor protected from the sea by a barrier beach. The explanation of this unusual topography is disclosed at low tide, in a line of stumps and prone logs along the water's edge, the stumps in the position in which the trees grew. These [facts] show that our salt

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[1] Hitchcock, Edward, Report on the geology [etc.] of Massachusetts, Amherst, 1833, p. 39. The geological map accompanying this report shows by symbols five localities, one of which, near Yarmouth, appears to lie within the area of salt marsh; but the salt marshes may be underlain by fresh-water swamp accumulations, as they are farther north, along the coast.

[2] Bartlett, H. H., The Chamaecyparis bog at Woods Hole, Massachusetts, Rhodora, Journal of the New England Botanical Club, **11**, Dec., 1909, pp. 221–235. Pl. 82 shows the shore line of a submarine bog at low tide. See also C. H. Shaw, The development of vegetation in the morainal depressions of the vicinity of Woods Hole, Bot. Gaz., **33**, 437, 1902. *Chaemaecyparis* is the *Cupressus* of older botanical works. *C. thyoides* is the white cedar of the coastal swamps of Massachusetts.

[3] Bartlett, H. H., *loc. cit.*, pp. 224–225.

marsh is a peat bog which the sea has invaded, not a tidal flat built up through the usual agencies of salt-marsh formation.

The bearing of this bog on the problem of subsidence of this part of the coast is considered farther on in this report. Johnson[1] states that he spent a day in making soundings in the bog and found long pieces of wood that were evidently logs or branches.

In a brief restatement of the argument for subsidence at Quamquissett, Mr. Bartlett published the data given him by the Coast and Geodetic Survey concerning the tidal range at this harbor. Spring high water stands 2.4 feet above mean sea level, mean high water, 2.0 feet above mean sea level. The highest tides rise 3.0 feet above mean sea level.[2]

SUBMERGED TREE STUMPS

In 1893 W. M. Davis observed the "diverging roots of a dozen or more trees" in an old swamp soil "below the beach sand and gravel at low tide just west of Bass River, a mile from the village of South Yarmouth." The soil of an old swamp containing stands of trees was seen west of Succonnesset Point. This swamp was separated by a beach ridge from an existing swamp.

The facts made known at Quamquisset indicate the probable existence along the coast of other similar bogs, such as proved to be of economic value on the coast of Cape May County, N. J., in the middle of the nineteenth century. Cedar logs were profitably mined from ancient swamps in New Jersey in 1857.[3]

In 1841 Edward Hitchcock reported that a "submarine forest" containing stumps of cedar occurred off Yarmouth, on the north side of the Cape, and extended more than 3 miles into the bay. He was also informed that a similar submarine deposit lay in the bay of Provincetown "on the side opposite the village."[4]

In his account of his travels on Cape Cod in the years 1849 and 1855 Thoreau says that he found peat pebbles on the beaches. He also quotes an old oysterman as having seen cedar stumps "as big as cart wheels" on the bottom of Cape Cod Bay three miles off Billingsgate Point.[5]

A fisherman whom I met on the shore of the Province Lands just south of the entrance to Hatches Harbor in 1915 told me that stumps of "pine" had been seen off that point below high water mark and that on the outer bar, in from 18 to 20 feet of water, the fishermen who drive down piles 40 to 50 feet long in constructing their fish traps, encounter a layer of peat. From his account of their use of the sand pump in sinking the piles until they reached the tenacious peat bed, I infer that the bed of peat is now about 30 feet below sea level.

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[1] Johnson, D. W., Botanical evidence and the problem of recent coastal subsidence, Botanical Gazette, **56**, p. 467, 1913.

[2] Bartlett, H. H., Science, **33**, p. 31, 1911.

[3] Kitchell, William, Geology of the County of Cape May, State of New Jersey, Trenton, pp. 77–83, 1857.

[4] Final report on the geology of Massachusetts, p. 308.

[5] Thoreau, H. D., Cape Cod, p. 183, Boston and New York, 1914.

Mr. Gilbert R. Payson, Jr., who has a summer home on Pochet Island, informed me that owing to changes in the spring of 1919 the beach about half a mile south of Little Pochet showed at low water in May the surface of an old marsh. This surface retained clear traces of old cart tracks and the footprints of oxen filled with sand. Mr. G. R. Payson thought that these impressions were made when the surface of the marsh lay inside the barrier beach, fully half a century ago.

Waterworn slabs and pebbles of compact peat are often thrown up on the beaches near Highland Light and elsewhere on the Cape, and fishermen tell of submerged forests in water off the coast.

MARINE MARSHES

Wherever shallow tideways are found on Cape Cod there are marine marshes, in which the saltwater vegetation that forms the surface may be underlain by freshwater swamp deposits. Extended study by borings made in the marshes about Boston by C. A. Davis suggests that similar vegetal deposits lie along the coast of New England. If the condition at Quamquisset is typical the salt marshes in bays and creeks are relatively thin mats of not very ancient date, and a special survey of these areas must be made before a scientific report on their nature and contents can be prepared, for it is no longer reasonable to assume that the marine deposits hold their surface characters down to the bottom on which vegetal growth began to take place. The State map shows by appropriate symbols the marshy areas.

The largest stretches of marsh lie on the outer part of the Cape, behind the barrier beaches of Chatham and Nauset, in the creeks and coves about Wellfleet, and in the drowned hollows of the highlands farther north, to Truro. A small tract surrounds the old headland of the Cape at Pilgrim Heights, or High Head. Barnstable harbor is the site of the largest marsh on the south shore of the bay. Innumerable strips of marsh lie behind barrier beaches on the inside of almost every cove and creek in the district.

Henry Mitchell states that most of the areas occupied by marshes have not been greatly increased or decreased since the coast was first mapped with any attempt at detail in 1880.[1] The marsh has evidently encroached upon certain shallow waterways, such as the inner harbor at Wellfleet, where, owing to the abandonment of the harbor by commerce, the inwash of detritus has formed mud flats upon which a new marsh is now vigorously growing (see Pl. 37, fig. 1). The passage through Boat Meadow Creek into Town Cove, in Orleans, through what is known as Jeremiah's ditch, is now a marsh drained by the ditch. The ancient records of boundaries on the Cape refer repeatedly to marshes whose landward edges appear to be now little changed after nearly two and a half centuries. In the steep-sided coves of the glacial ice-block holes, however, a change of several feet in level would be necessary to produce a perceptible horizontal displacement of the line of contact of the marsh with the mainland, except in the bottoms of shelving valleys. There is no tradition among the inhabitants that the marshes have spread into the land. Such change as may be taking place is so slow and continuous as to escape observation in a generation.

The swamp and marsh deposits now seen in such old channels as those about Wellfleet, in Pamet River, were probably once tidal ways like the bays and coves at Chatham Oyster Pond, the Mill Pond, and Rider's cove, for the old cliffs that border these marshes must have been produced by the undermining of their bases at sea level, either by waves or by strong tidal currents. Such a cliff is that in the drift standing in the marsh back of Wellfleet village. The cliffs in the inner part of these hollows and valleys would probably not have been formed if the vegetal deposits in the glacial depressions had been accumulated by the slow submersion of the district and the consequent increeping and upbuilding of the swamps and marshes from initial coastwise strips that started behind long barrier beaches and bars at the mouths of channels.

The Pamet marsh, above the village of Truro, and the "salt meadow" on the north side of High Head have been cut off from the sea on the west by dikes.

PEAT DEPOSITS

A knowledge of the value of peat as fuel and fertilizer appears to have been brought to the Massachusetts and Plymouth colonies by the first settlers. A discussion of the origin of peat and its use in the form of ashes as a manure appeared in 1797.[2]

[1] Mitchell, Henry, Notes concerning alleged changes in the relative elevations of land and sea, U. S. Coast and Geodetic Survey Report for 1877, Appendix No. 8, p. 5, Washington, 1880.

[2] Deane, Samuel, The New England Farmer and Georgical Dictionary, pp. 253–254, 1797.

Post-Glacial Changes of Level

No evidence is available to show changes in the level of the sea since the ice sheets in this region disappeared. The marine shells that are scattered through the soil or that lie in small heaps along the coast were gathered by man, or isolated shells were laid down by sea birds. Farmers have brought from the beach and spread on the land kelp containing the exuviae of mollusks and crustaceans, and have thus added to the shells scattered over the surface. Such shells and shell heaps afford no evidence of changes in the level of land and sea, but they must not be confounded with the outcropping older shell deposits found in the beds of the Cape. Shells that are encountered in wells are significant if they are considered in their proper relations to the older deposits of the glacial epoch. No known natural deposits of the shells of existing animals have been found above the level of the sea.

Likewise the surface deposits of Cape Cod that lie above the recognized beaches and marine marshes reveal no traces of the action of the sea except, possibly, those that stand above the reach of high tide and that are reached by the waves in great storms, such as the Minot Gale of 1851 and the storm of November, 1898, when the sea rose some 18 feet above its normal level in Barnstable. In the Minot gale the sea rose 17 feet above mean high water on the outside of the beach near Scituate, on the west shore of the Bay. Although such a temporary rise of the water may make changes in the beaches, bars and dunes and may do much damage to the vegetal growth in salt marshes, it leaves little impress upon the drift at the back of the shore and marshes. At Barnstable, where the storm water rose so high in 1898 as to reach the main road in the village, I was unable in 1916 to detect in the configuration of the land any recognizable trace of the action of the sea above the customary range of high tides. A minute examination of the gravel and sand about fixed boulders that stand within the range of rushing water may disclose signs of scour. The topography, position, and elevation of the sand plains, together with their dry stream creases and kettle holes and ice-block holes are all phenomena formed in the presence of melting glaciers and indicate rather the absence of the sea than its presence above their bases. The kettle holes, many of which are sharply defined and little changed in contour by the wash of gravel and sand about blocks of ice, give no hint that tides and currents poured through the creases which connect many of them with the base level of drainage.[1] The absence of inbuilt deltas, bars, and shore phenomena at an old sea level in these basins lends no support to the supposition that they have come up from the sea since the present surface was formed. Careful scrutiny of the surface of Cape Cod and the country south of Boston by several competent geologists has failed to disclose beaches that lie beyond the reach of storm waters, or other evidence of marine action that indicates changes in the level of the sea since the end of the glacial period, or during or after the retreat of the last ice sheet.[1]

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[1] Woodworth, J. B., An attempt to estimate the thickness of the ice blocks which gave rise to lakelets and kettle holes, Am. Geologist, **12**, pp. 279–284, 1893.

Before the stratified glacial deposits of this district were properly interpreted they were called "modified drift," a term which implied that they had been modified by some agency other than that which produced them. The modification was by some supposed to be due to the action of the sea. Many geologists, including Shaler, held that the outwash plains of gravel and sand on Cape Cod and the neighboring islands had been laid down beneath tidal waters.

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[1] Woodworth, J. B., Some glacial wash plains of southern New England, Bull. Essex. Inst., Salem, Mass., **29**, 1897 (actually issued 1899), pp. 71–119. At p. 105 some evidence against deposition of sand plains at sea level is presented. The accompanying bibliography includes the titles of several papers on changes in sea level in Massachusetts and Rhode Island.

CHAPTER II

GEOLOGY OF THE ELIZABETH OR GOSNOLD ISLANDS

(See Plate 3)

INTRODUCTION

The Elizabeth Islands lie between Buzzards Bay and Vineyard Sound and form an extension of the Falmouth moraine southwestward from Woods Hole. Their geography and geology have been briefly described by Shaler and Hollick. They form a part of Dukes County and of the town of Chilmark. They bear aboriginal names, which have been spelled in different ways.[1]

Naushon, with the small appendages at its east end, is about 9 miles long. It is separated from the mainland at Wood's Hole by a narrow tidal passage, which is navigable by local Sound Steamers. Pasque Island, which is next westward in the group and hardly twice as long as it is wide, is separated from Naushon by a narrow tidal way known as "Robinson's Hole." Across "Quick's Hole," on the southwest, lies Nashawena, the second largest island of the group. It is somewhat more than 3 miles long. At the west end of the group stands the island of Cuttyhunk, which is about 2 miles long. It is the site of the first attempted English settlement in New England, that of Gosnold, made in 1602. A reef of glacial boulders still farther southwest forms the dangerous "Sow and Pigs," a dangerous reef on which there is a lightship.

Northwest of the main line of these islands there is an imperfect second line of small islets, of which Penikese, lying north of the east end of Cuttyhunk, is the largest. Off the southeast point of Penikese there is an islet of glacial drift, and near the east end of Naushon there is a group of three islets known as the Woepeckets, which trend northeastward.

The bed-rock floor beneath the islands is presumably an extension of the granite-gneiss, diorite, and schist found about New Bedford. None of the wells put down on the islands appear to have reached this floor. A well on Cuttyhunk was bored to the depth of 230 feet without striking bed rock. Three-fourths of a mile north by west from Penikese the bottom of Buzzards Bay reaches a maximum depth of 126 feet in a depression extending southwestward to another maximum depth of 135 feet at a distance of one and three-fourths miles west by south of the island. Another deep hole lies north of the west end of Pasque island, opposite the entrance to Quick's Hole. These irregular depressions are possibly of glacial origin and probably do not reach bed rock, which was not reached by a well 120 feet deep on Penikese Island. The southeastern slope of the bed rock surface on the northwest side of Buzzards Bay is too poorly exposed to afford a trustworthy estimate of the inclination of the bed rock floor beneath the Bay and so on under the Elizabeth Islands. This bed rock floor, however, appears to slope southeastward at a rate as high as 19 feet per mile. Such a slope would carry it just beneath the deepest wells reported on Naushon and Cuttyhunk. The slope doubtless exceeds 20 feet per mile, and the surface is probably not an even floor that lies at a depth 250 feet or more beneath the Elizabeth Islands.

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[1] Hayward, John, A gazetteer of Massachusetts, Boston, 1847. The position of the islands in relation to the surrounding waters and the soundings of the sea bottom are shown in Chart No. 112, of the U. S. Coast and Geodetic Survey, on the scale 1/80,000. Chart No. 249 shows the coastline of the islands (but not the interior) on the scale 1/40,000. Detailed maps of the islands have also been prepared as follows: Cuttyhunk including Penikese, Chart No. 297, scale 1/10,000; this map includes the western end of Nashawena. Chart No. 345, Pasque Island, and shores of Naushon and Nashawena islands bordering the tidal passages, Quick's hole and Robinson's Hole. Chart No. 348 shows Nonamesset Island and Woods Hole; scale 1/10,000.

The surfaces of the islands bear coarse glacial drift and large erratics, chiefly of granite and diorite like that of the neighboring ledges on the north shores of Buzzards Bay. The drift here and there assumes the form of low ridges arranged in loops and festoons. These ridges are small frontal moraines of the retreatal type, and the whole morainal deposit forms a thin veneer over a thick layer of yellowish sand and blue clay, which makes up the great bulk of the deposits of the islands above sea level. These stratified beds appear to be the counterpart of similar beds of sand and clay on Cape Cod and the islands on the south. Their obviously eroded surface and their stratigraphic position beneath the moraine indicate their formation prior to the later Wisconsin stage and probably to the whole of that stage. They appear to be the equivalents of one or more of the formations exposed on Marthas Vineyard as low down as the Gardiners clay, exposures of which are probably represented by the beds of blue clay seen along the shores of the smaller islands west of Naushon. As Cretaceous beds are exposed on Nonamesset, at the east end of Naushon, it seems possible that the entire Pleistocene section comes to the surface at one place or another beneath the later drift cover. It would be difficult to identify beds, however, where so much depends upon the vertical succession of formations of glacial origin.

The gaps through which the sea flows between the islands differ in no way essentially from low places above sea level on the larger islands, such, for instance, as those on Naushon. These depressions appear to be of pre-Wisconsin age and to have been formed by erosion and somewhat modified later by the action of ice. Deposition of morainal drift, however, is more evident than glacial scouring, though here and there the effects of the action of running water may be seen in winding creases that lead away from old ice fronts marked by morainal ridges.

The chain of islands has a strong morainal cast and conforms in trend with the lobate margin of a protrusion of the ice sheet in the Buzzards Bay depression and in the main owes its origin to the crowding up of the underlying coastal plain deposits and older Pleistocene gravel, sand, and clay, yet the stage of Pleistocene glaciation at which the deformation was accomplished is not clearly indicated. Here, probably, as on Marthas Vineyard, several successive ice thrusts were effective in the shaping of the islands.

A small exposure of Cretaceous and Tertiary beds lies at the east end of the group. These beds are tilted and show a strong deformation. Such beds have not been recognized as the southwest end of the group, where a well boring goes over 200 feet below sea level.

The absence of outwash plains of gravel and sand on the south side of the islands is evidently not to be explained by supposing their erosion and removal by the sea. It may mean that the stream flow was not sufficiently strong to carry sand and gravel to a great distance from the ice front. Soundings in Vineyard Sound and in the adjacent waters between Gay Head and Block Island do not show the presence of such deposits.

NAUSHON

Salient Features

Naushon, the largest island of the Elizabeth group, is 8½ miles long and between 1 mile and 1½ miles wide. It extends southwestward and is separated from Pasque Island, on the southwest, by Robinsons Hole, a narrow tidal passage having a minimum depth of 13 feet at mean low tide, and from several small islets — Uncatena, Nonamesset, Rams Head Island, East Buck Island, Monohansett Island, and three islets unnamed on the Coast Survey chart — by shallow tidal ways due to depressions in the moraine. Woods Hole, a tidal passage navigable for small steamers, separates Naushon and its dependent isles from the heel of Cape Cod at the port of Woods Hole.

The topography of Naushon and the adjacent islands is morainal. The higher hills in the interior of the Naushon rise to elevations ranging from 100 to 168 feet. A broad depression just west of the middle of the island gives rise to coves on the opposite shore of the island. Tarpaulin Cove, on the southeast side, is a well known anchorage in northeast gales for sailing vessels passing through Vineyard Sound. Naushon remains largely covered by a native forest, which corresponds closely with that growing on these islands when they were first explored by white men. The soil is prevailingly sandy and the surface is encumbered with glacial boulders, some of them large and assembled in picturesque groups.

Hollick[1] has given a sketch of the glacial deposits of Naushon. He found on the south shore of Nonamesset Island, near its east end, a bed of Cretaceous lignitic and noduliferous parti-colored clay, and he gives a hypothetical cross section of Naushon showing overthrust Cretaceous beds surmounted by bouldery moraine.

The forest comes down to the wind-swept shores in a bushy cover that dwindles to a low scrub growth of plants and that protects the trees from the harsh winds that strike the island. Plate **37**, fig. 2, gives a view of the open forest, free from undergrowth, as seen from a point on the south shore east of Tarpaulin Cove. In this primeval forest deer keep down the undergrowth. The flora appears to have come from the mainland and not from the islands on the south, for Vineyard Sound has doubtless been an effective barrier to the migration of plants between Marthas Vineyard and the Elizabeth Islands.

Cretaceous Deposits

The geology of Naushon was briefly described by Shaler,[2] who recognized, beneath the surface moraine, a thick mass of fine sand, to which he had already given the name ''Naushon series,'' comparing it with the beds now referred to the older Pleistocene on Marthas Vineyard.

Cretaceous beds are exposed on the south side of Nonamesset Island at the base of a small hillock that forms the eastern headland of Lakey's Bay. The surface here carries large boulders, one of gneiss having a length of 18 feet. Farther east, along the bluff facing Vineyard Sound, gravel that appears to lie in beds that dip gently northwest is seen under a gray till having a compact clayey matrix. A bed near by contains light, fine-grained sand. A section farther east, about 20 feet high, reveals, beneath a top of gravelly, clayey till, a bed of gravel underlain by a fine yellow sand. A few feet farther east a lignitic Cretaceous bed rises about 6 feet above the limit of marine action. This bed discloses the following section, the layers being named from above downward:

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[1] Hollick, Arthur, A reconnaissance of the Elizabeth Islands, Annals N. Y. Acad. Sci., **13**, pp. 387–418, pls. viii-xv, 1901.

[2] Shaler, N. S., Geology of the Cape Cod district, U. S. Geological Survey Eighteenth Ann. Rept., 1896–97, Part II, p. 543, 1898.

Cretaceous beds on Nonamesset

Black lignitic clay containing some lignite.
Pinkish gray clay containing a sandy iron-stained layer that furnishes the ferruginous concretions seen on the beach.
Quartz gravel.
Light yellow sand.
Lignite underlain by clay imperfectly exposed.

MIOCENE GREENSAND

About two rods east of this bed is a Pleistocene section, which is underlain by a layer of yellowish greensand, a mixture of quartz grains fairly well rounded, and a few black, rounded nodules such as are found in the Miocene greensand bed on Gay Head, probably the altered casts of foraminifers. Still farther east the nodule-bearing Cretaceous clays reappear at the edge of the beach.

PLEISTOCENE SECTIONS

Between the points just mentioned the Pleistocene section exhibits various features in different thin deposits.

Pleistocene section on Nonamesset Island

	Feet
Bouldery surface drift	1–3
Uncomformity	0
Fine, light sand	4
Zone of angular blocks of granite, etc.	1–4
Till (?) A gravelly unstratified clay	4
Gray, streaked sand, which grades downward into ferruginous red sand	3–4
Coarse glacial gravel	6+

These glacial deposits resemble in character and succession the older Pleistocene beds just above the Cretaceous and Tertiary beds in the Gay Head cliffs. They include deposits formed at stages as late as the second ice advance here recognized. The beds are tilted, and the surficial bouldery drift of the Wisconsin stage is only a veneer over a mass of older Pleistocene deposits.

Most of the boulders on Nonamesset are of granite-gneiss, some of which contain traces of banded schist.

Several years ago boulders were struck at a depth of 80 feet in wells bored at the east end of Naushon, near the dwellings of the late Commodore Forbes. These boulders may represent the Montauk till, or one of the lower boulder beds encountered on Marthas Vineyard. The entire assemblage of gravel and coarse and fine sand that appear above sea level in small exposures in the central and western parts of the island closely resembles the Manhasset formation and the underlying Jacob sand. On the east side of Ram's Head, the west chop of Kettle Cove, a bed of fine sand that dips westward is exposed. Similar beds of sand may be seen in broad, wind-bared exposures in the interior of the island, in the "sheep pasture" northeast of Tarpaulin Cove, and in the depression between Tarpaulin and Kettle coves, on the northwest side of the island.

LATE WISCONSIN OR FALMOUTH MORAINE

FRONTAL MORAINE

The frontal moraine on the Elizabeth Islands is an extension of the Falmouth moraine in the frontal outcurved lobate margin of the ice lobe that deployed over Buzzards Bay. As seen in the few exposures along the shore and at places in the interior of Naushon the material of this moraine is very thin. In these exposures beds of till 3 or 4 feet thick overlie beds of fine sand. At many places in the interior of the island the later Wisconsin drift appears as isolated boulders resting in the sand or as morainal belts of boulders that dominate the surface.

The large ridges in the relief of Naushon, which run nearly parallel to its long axis, have a decidedly morainal aspect, but the topography as a whole suggests that they originated as much by the deformation of the older Pleistocene beds as by direct erosion or by being mantled by new deposits during the last ice invasion. Here and there downward slopes that form vales which widen toward the sea suggest the action of running water, such as is evident on Marthas Vineyard and other islands of the outer group, during the interglacial stage preceding the Wisconsin glacial advance. The most conclusive evidence that an ice front extended along the axis of Naushon is seen in the numerous small ridges of boulders and bouldery drift at places on the island where the removal of the forest has exposed the surface to view. In the "sheep pasture" on the hills about a mile or more northeast of Tarpaulin Cove, where the Wisconsin drift forms a relatively thin veneer over Pleistocene yellowish sand. the moraine rises into low, somewhat inosculating bouldery ridges containing scattered large boulders. (See Plate 38, fig. 1.)

The island appears to be a broad, low ridge, which rises rather steeply from the sea, especially on its southeast side, and then more gently toward its middle rolling hills. The axial ridges become lower toward the southwest in the direction of their length, and are discontinuous, but their massiveness is disproportionate to the details, such as the bouldery ridges, and the kettle holes which here and there interrupt the surface, and which were formed by the action of ice.

KETTLE HOLES

The kettle holes on Naushon are typical morainal features and they were probably produced by the melting of buried blocks of ice or of outlying parts of the ice front that were encumbered by drift. They have been mapped in detail by Mr. B. F. Koons.[1]

Most of the kettle holes are in the morainal upland and show no relation to the ice front and no alignment of their longer axes to the direction of the motion of the ice. In the middle of Naushon there is a crowded group on the northeast side of the large ("Grinnell") swamp, which is an extension of the depression forming Tarpaulin Cove. Many of the kettle holes are occupied by small pools or swamps. Mary's Lake, at the east end of the island, is a deep-sided kettle hole, from which an ice block has melted out. The depth of some of these ice-block holes would seem to indicate the deposition around their sides of the sand and gravel that underlie the till. In a frontal moraine that is subject to the pressure of ice, blocks of ice may behave very much as large boulders and may become so much involved in movements of the ice sheet and the underlying terrane as to assume forced relations with older displaceable material. Ice blocks evidently lay out in old channels or shallow valleys on the south side of Cape Cod and were surrounded and probably covered by deposits. The glacial trough on Naushon that extends from French Watering Place inland to the west side of Tarpaulin Cove is the site of a remnant of ice, signs of which are shown in the swamp and central lakelet near its east end. On Cape Cod the blocks of ice that gave rise to kettle holes in the outwash plain and in the moraine, as at Brewster, were remnants of the sheet that advanced to the outer line of islands. The same conditions doubtless prevailed on Naushon and the Gosnold islands generally, so that the ice blocks were worked over by the front of the ice when it lay along the crests of these islands.

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[1] Koons, B. F., Upon the kettle holes near Woods Hole, Mass., Am. Jour. Sci., 3d ser., **27**, pp. 26–264, 1884. Also additional notes on the kettle holes of the Woods Hole region, Mass., Am. Jour. Sci., 3d series, **29**, pp. 480–486, 1885.

GLACIAL ERRATICS ON NAUSHON

Some of the numerous glacial boulders on Naushon are grouped in huddles or lines. In places along the shore where the finer drift has been washed away boulders have been heaped up in irregular piles by the waves, as for example, about a mile northeast of Tarpaulin Cove (Plate **38**, fig. 2). Large flattish boulders that are piled up along the coast have a dip seaward that shows the action of storm waves. Boulders 6 feet long have been thus thrown up by the storm waves of Vineyard Sound. Boulders of conglomerate derived from Carboniferous rocks around Middleboro are rare on the island. Most of the boulders appear to have been brought from the pre-Carboniferous gneiss, schist, and diorite about New Bedford and beneath the waters of Buzzards Bay.

Among the rocks seen were a coarse-grained schistose diorite; an aplite dike rock in contact with blackish schistose hornblende granitite; a black actinolite rock; a gray granite-gneiss carrying large inclusions of a subrounded fine-grained dark rock, possibly diorite; a large boulder of coarse-grained pepper-and-salt diorite containing veins of epidote and coarse dioritic segregations; a fine-grained diorite containing intrusions of granitic rock; a diorite breccia enclosed in granite like that at Little Nahant; a mass of fine-grained aplite (?) enclosing angular blocks of a coarse, gray hornblendic granitite; a brownish, massive semi-schistose rock containing aggregates of hornblende in drawn-out bunches, and a gneiss containing well defined crystals of feldspar that weather out and leave pits 1½ inches across. One hornblende-granitite block exhibited a dike of fine-grained basic rock, which showed a gneissic structure formed by shearing along a fault zone. One cobble of diabase was seen.

A comparison of these rocks with those found north of Boston, near Worcester, and around the head of Narragansett Bay indicates that the area around New Bedford and probably the islands are underlain by a group of chiefly igneous rocks that were intruded in probably the following order:

1. Dioritic schist (possibly a metamorphosed phase of No. 3).
2. Granite-gneiss carrying shreds and blocks of No. 1.
3. Diorite of second (?) intrusion.
4. Hornblendic granitite with aplitic and pegmatitic dikelets, some enclosing brecciated facies of the mother rock.
5. Aplite dikes of No. 4, contemporaneous or later.

The schistose rocks in the area around New Bedford, which were separated from the Carboniferous rocks and the granites by Edward Hitchcock in 1841 and by me in 1899[1] have not been identified lithologically in the field, and their lithological character is not shown on the geological map of the State. The complex of rocks described above corresponds apparently with the supposed Devonian igneous rocks of Emerson.[2] The hornblendic granitite is probably the same as his Dedham granodiorite and Milford granite. The granite-gneiss would thus become the correlative of the Northbridge granite-gneiss of Emerson, which is referred to the Archean and lies below an Algonkian (?) quartzite. The aplite becomes the associate of the Milford granite, and the fine-grained dioritic rock, although it is subject to further examination under the microscope, would appear to be the equivalent to the Ironstone quartz diorite of Emerson. The area about New Bedford is shown on Emerson's map as an extension of the Dedham granodiorite, whose various phases, which grade toward aplite on one hand and diorite on the other, include local sheared strips of the rock forming "gneiss."

Many large boulders may be seen in the interior of Naushon. Koons measured two erratics, each 27 feet long. A large, roundish boulder about 30 feet long, surrounded by small boulders, lies on the crest of the island, in the middle one of three strong ridges, northeast of Tarpaulin Cove.

Many boulders lie along the shore of Kettle Cove. A large boulder of gneiss on the beach on the east side of Ram's Head, at the west point of the Cove, bears on its western sloping surface glacial grooves running N. 20° W. by the compass, or N. 33° W. by true bearing. This boulder may therefore bear the marks of the ice that ran over it during the last stages of the ice on the island. On Ram's Head also there is a large boulder that has split along a joint plane, so that its upper half has slid down to form a small rock shelter, which is invaded by the sea at high tide.

About half a mile west of French Watering Place and a third of a mile inland from the shore there are two large boulders about 30 feet long, one of which is broken into three blocks.

A large boulder on the beach at the base of the 80-foot hill about a quarter of a mile northeast of the east chop of Tarpaulin Cove stands out several yards from the present bluff. It is inclined landward as if it had slid down the bluff from the surface when the coast stood farther out. This boulder is rather too large to have been thrown back by sea waves.

Somewhat east of the central point of Nonamesset there is a boulder 24 feet long, which stands at least 9 feet above the surface of the bouldery drift. Koons noted another larger boulder near by. These large boulders appear to be a part of the Wisconsin drift.

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[1] U. S. Geological Survey, Monograph XXXIII.

[2] Emerson, B. K., Geology of Massachusetts and Rhode Island, U. S. Geol. Survey, Bull. 597, pp. 164–185, 1917.

AGATE PEBBLES

On the south coast of Naushon, west of Tarpaulin Cove, pebbles of brown and white banded agate are rather common on the beach. These pebbles have evidently been washed out of the morainal cliffs along the coast. Similar pebbles are found on the beach on Marthas Vineyard, but Tarpaulin Cove is probably about the eastern limit of their distribution in the Elizabeth Islands. An occasional pebble of agate on Naushon encloses fragments of a reddish shaly wall rock resembling certain phases of the Carboniferous Wamsutta formation seen about Attleboro, but these agate pebbles appear to have been derived from some locality south or east of Attleboro. Boulders of the peculiar ilmenitic iron-ore of Cumberland Hill, in Rhode Island, some 5 miles northwest of North Attleboro, have been carried to Gay Head by glacial action in at least one of the older Pleistocene stages of glacial invasion. The general direction followed by these pebbles is S. 40° E., and Tarpaulin Cove, on Naushon lies in the same direction from Diamond Hill, northwest of North Attleboro. This hill includes a large mass of quartz that appears to contain veins of similar agate. Other smaller veins are found near by in the red Carboniferous rocks. Along with the agate pebbles on Naushon there are numerous pebbles of white quartz that contain small cavities beset with minute quartz crystals. Possibly the source of the quartz and agate may prove to lie near Diamond Hill. Similar agates have been found on the beaches on No Mans Land and Block Island.

PASQUE ISLAND

Pasque Island lies west of Naushon and is separated from it by a narrow passage, Robinson's Hole, which at its narrowest point is little more than 500 feet wide. The island is about a mile wide from north to south and about 1½ miles long from east to west. This measurement does not include the barrier beaches and a small swamp and land-tied islands at the southeast end of the island. Several drift-covered knolls in the eastern part of the island rise to a height of about 100 feet and a middle ridge of the same height extends westward toward a point exceeding a height of 120 feet, from which it is separated on the north by a steep-sided glacial depression. Between the medial ridge and a lower one on the north coast there is a small kettle hole containing a lakelet. Similar lakelets are seen at the east and west ends of the island, either in the glacial drift or behind barrier beaches thrown up by the waves.

The island is covered with bouldery drift of the Wisconsin stage, in which there are numerous kettle holes, 30 to 50 feet in diameter, which contain lakelets or swamps. The north coast is covered with drift. On the steeper and more exposed south coast, Mr. Gilbert Hart, my assistant, observed a cut in the bank showing 4 to 8 feet of till covered by a bed of sand 4 feet thick, under which 3 feet of clay was exposed down to the base of the bluff.

At the east end of the island, between the two small ponds shown on the map, clay has been dug. The till at this point is little more than a coating of scattered boulders embedded in a sandy soil or subsoil one or two feet thick. Well defined waterlaid sand, 3 to 4 feet thick, underlies this till and is underlain by the clay. This clay is probably underlain by pre-Wisconsin drift, as is shown more clearly on Nashawena.

A small islet of glacial drift off the southeast end of the island supports bars that tie it to the main island and enclose a small marsh. A barrier beach thrown up on the north coast encloses another small marsh. The beaches are largely bouldery.

NASHAWENA ISLAND

The island of Nashawena, the second largest in the group, is about 2½ miles long and from three-fourths of a mile to 1½ miles wide. Its glacial features — its ridges of older Pleistocene sand, its long hollows, and its kettle holes — are essentially the same as those of Naushon. Most of the broader ridges are in the southwestern part of the island, where at three places they rise to heights exceeding 120 feet. A deep depression lies in the western part of the island. Here the steep slopes on the east, south and west sides of a small glacial lakelet show that it was formed by an ice block or a tongue of the ice sheet. Two depressions on the south side, which extend southeastward down to sea level appear to mark the path of a glacial stream.

The north coast of the island is covered with till or, where the sea has formed cliffs, with a talus of bouldery drift. At several places on the south coast, where steep bluffs show that the sea has cut back the land, beds of clay that rise several feet above sea level may be seen. Most of the clay on the weathered surface is whitish, but that within the bed is blue or brown where it is oxidized, resembling the clay exposed on Cuttyhunk. The bed appears to be a phase of the Gardiners clay, which is much better exposed on Marthas Vineyard, Block

Island, and Long Island. Most of the beds are horizontal, and those along the south coast are covered by Wisconsin till, which at some places is 6 feet thick.

After a heavy rain in September, 1916, which exposed a section in a gully near the east end of the bluff of the 100-foot hill at the west side of the channel that extends southeastward from the ice-block hole already described, my assistant, Mr. Gilbert Hart, measured the following section:

Section on the south coast of Nashawena near the middle of the island

	Feet	*Inches*
Till	4–6	0
Sand and clay		6
Glacial sand containing a layer of pebbles	1	0
Clayey sand		3
Fine sand		5
Coarse sand		10
Clay		1
Coarse sand and gravel		6
Ferruginous blue clay containing angular pebbles	3	0
Sand		3
Blue clay containing iron concretions	5	0
Fine sand	4	0
	21	10

The upper clay bed, which carries angular pebbles, appears to be till laid down in the presence of ice, possibly floating ice, and is like a similar bed of pebbly clay in a section of the older Pleistocene deposits on Gay Head. The ferruginuous bands and concretions in the clay are like those in the clay that lies below the Gardiners clay. Exposures of the similar beds of clay were seen at a few places on the northeast coast of the island.

At the east end of the island, which faces Quick's Hole, there are two ponds of brackish water, which are partly enclosed by bars that have tied a small islet of drift to the main island.

On the north side of the island a small ridge of bouldery drift projects westward into the sea, forming a small harbor. Two small islets of drift off the point at the west side of the ice-block hole already described appear to be a continuation of this ridge. Between these islets and the peninsula the entrance to the small harbor is obstructed by large boulders, and other boulders stand conspicuously around the northwestern point of the island and about the northeast point, at the entrance to Quick's Hole.

A small marsh surrounds the ponds at the east end of the island, and the lakelet in the ice-block hole near the middle has been encroached upon by a swamp. Other small swamps lie in the bottoms of kettle holes or in hollows behind the barrier beaches.

A small sand spit has been formed by the currents at the west end of the island, where Canapitsett channel separates the island from the appendages of Cuttyhunk. The shore seems to be retreating very slowly as compared with that of the islands which face the open sea. Talus conceals most of the cliffs, and the sea probably does not accomplish much erosion except during unusually heavy winter storms.

CUTTYHUNK ISLAND

Cuttyhunk is the outermost of the Elizabeth Islands. John Brereton described it in a paper published in 1602. He writes, ''it containeth many pieces of necks of land, which differ nothing from several islands, saving that certain banks of small breadth do like bridges join them to this island." Brereton's statement that the island was then sixteen miles in circumference could be true only if Nashawena were included in his measurement. Canapitsit channel may then have been closed by a bar. On Southack's chart drawn somewhat more than a century later, Cuttyhunk and Nashawena are represented by a single island, but this chart is not reliable evidence concerning such details as the opening and closing of bars across inlets. Brereton described the lake at the west end of the island as ''almost three miles in compass," a measurement that is too large for the present body of water called West End Pond, but the lake may have extended considerably farther north in 1602, the barrier beach on that side having since been driven in by erosion.

A small island in West End Pond, named Gosnold's Island on the charts, was the site of Captain Gosnold's house, erected in 1602. Gosnold arrived from England in the *Concord* about the middle of May, 1602, and abandoned his attempt to found a colony after staying a month on Cuttyhunk, which he called Elizabeth Island, and sailed for England on June 17.[1]

The island, which is now deforested, was in Gosnold's time covered, apparently in its central part, with an open growth of trees, which, according to Brereton, included oak, cedar, beach, elm, holly, and walnut in abundance, and some sassafras. The low outer parts of the island appear to have been grass land, as they are now. Here, as on Block Island, where the original forest was cut away by white men for fuel or for timber, trees cannot survive except in the lee of some protective barrier of lower, hardier bushes, or of hills.

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[1] See Winsor, Justin, Narrative and critical history of America, **3**, pp. 172–173, 187, 1884. John Brereton's letter to Sir Walter Raleigh giving an account of his voyage under Gosnold, entitled "A Briefe and true Relation of the Discoverie of the North Part of Virginia," etc. (London, 1602), was reprinted in the Massachusetts Historical Collections, 3d series, **3**, pp. 85–93; and again (with some omissions) by Thomas Wentworth Higginson in his ''Young Folks book of American explorers," Book X, pp. 201-213, New York, 1894.

Cuttyhunk now consists of a central round hill of glacial drift, which rises 136 feet above the sea in its highest morainic knobs and ridges. These are flanked on the southwest by a lower mass of glacial drift, which has a different contour and has been much cut away by the sea on the south and west. An extension of this drift forms a barrier beach enclosing West End Pond, near the western shore of which lies the small islet on which Captain Gosnold attempted to form a settlement. Another low glacial deposit that lies northeast of the central mass of the island would form a separate island were it not for the bar that ties it to the main mass. Hooked spits that stretch out from the shore partly enclose a salt lagoon known as Cuttyhunk Pond. The bar or barrier beach on the south side of this pond extends from Cuttyhunk toward Nashawena and ends in a small mass of drift that borders Canapitsit channel.

The central round morainal hill of the island bears ridges that trend in the general direction of the group of islands and that consequently lie nearly parallel to the old ice fronts along which they were formed, either by pressure and displacement of the underlying beds or by the formation of frontal deposits. Many of the depressions here culminate in kettle holes, most of which contain small swamps.

The morainal ridges in the lower drift surface, which lies south and west of the main mass of the island and extends to its west end, rise to a height of 60 feet. These ridges front the south coast and show by their general rise in that direction that the land once extended a quarter of a mile seaward from the present cliffs. The detached deposit of drift in the northeastern part of the island rises to a height of about 50 feet and shows gently swelling glacial contours. In Gosnold's time this land appears to have been connected with the western part of the island by a bar, as it now is, and to have been the place referred to by Brereton as the bivouac of the savages described by him as "every night retiring themselves to the furthermost part of our island, two or three miles from our fort."

Geological Structure

The geological structure of Cuttyhunk is like that of the islands immediately northeast of it. Beneath the surficial morainal deposits of Wisconsin drift, which in places reach a thickness of 15 feet, and which bear scattered blocks of granite and gneiss, there is exposed above sea level along the cliffs a thin bed of sand overlying a blue clay. The clay at the surface is in places whitish, but that within the bed is ferruginous red. This clay is probably the equivalent of the Gardiners clay.

A well that was driven to a depth of 230 feet on the island passed through sand and blue clay. The water in this well rises to a height of 190 feet above the bottom of the boring.

Freshwater swamps occupy several small tracts on the island, the water being held up by the underlying clay. Saltwater marshes have been formed in the lee of the barrier beaches and around the shores of the salt ponds. The Coast Survey chart of 1853 shows West End Pond extending into confluence with a small pond that was cut off from it by a marsh as shown by the survey of 1889.

The southwest coast of Cuttyhunk is exposed to heavier attacks by the sea than any other part of the coast of the Elizabeth Islands and has therefore retreated rather rapidly since the first survey was made. A comparison of the chart of 1853 with that of 1889 appears to show that the south coast has retreated more than 130 feet, or at a rate of more than 3 feet a year. A few centuries ago the land must have extended farther south and west.

SOW AND PIGS REEF

A boulder-covered reef extends westward from the westernmost part of Cuttyhunk to a group of large boulders known as the Sow and Pigs, a map of which was made by Lieut. M. Woodhull, U. S. N., in 1853, which accompanies his report on the Sow and Pigs rocks.[1]

Lieutenant Woodhull states the Sow and Pigs rest on ''a bed of rocks and stones from the size of those generally used for paving, to boulders two or three feet in diameter.'' He says that the cluster which makes up the ''pigs'' forms almost a circle, about 50 feet in diameter, within which there is one to two feet of water at low tide. No. 1, or Saddle Rock, measured 14 feet in length, 7 in width, and 9 in height. Sow rock stands on the south slope of the reef in about two fathoms of water at low tide. The base of this rock, according to Lieutenant Woodhull, measured 15 by 20 feet, but the apex was visible only at low water. The Sow and Pigs reef is no doubt the site of a former islet, and the Middle

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[1] Woodhull, M., Upon the survey of the "Sow and Pigs" rocks, off Cuttyhunk, Massachusetts, with reference to the location of a lighthouse, Rept. Supt. Coast Survey for 1853, p. 172, Plate No. 5, Sketch A, No. 5.

Ledge and Whale Rock, which lie just off the west end of Cuttyhunk, are similar remnants of lost land that extended westward along the line of the Falmouth moraine. The name "Sow and Pigs" is on Southack's chart of the coast, and is undoubtedly a seventeenth century expression, like "Bishop and Clarks," "Rose and Crown," shoals that lie farther east, designating a large boulder and its surrounding smaller associates.

PENIKESE AND WOEPECKET ISLES

Three small islands, Penikese and Gull Island, which lie about two miles north of Cuttyhunk Island, and Woepecket Island, which lies about three-quarters of a mile north of the eastern part of Naushon Island, form an inner line of morainal heaps on the south side of Buzzards Bay.

Penikese Island

Penikese Island consists of a large and small islet of glacial till which are connected by a barrier beach. The larger island is about three-fourths of a mile long and somewhat over a quarter of a mile wide. Two drift hills in its central part rise to heights exceeding 80 feet. The eastern isle is not more than a quarter of a mile long from northeast to southwest and rises to an elevation of more than 60 feet. Its wave-washed shores are strewn with glacial boulders derived from till. The underlying deposits are presumed to be sand and clay similar to those under Cuttyhunk Island. According to Mr. Gilbert Hart, my assistant, who visited the island in September, 1916, there were then seven bored or driven wells on the island, one of which is 120 feet deep.

On the northeastern coast of the main island Mr. Hart observed a bed of till 7 feet thick, which lay upon sand. Boulders are abundant on the surface of the island. Most of them are granitic, but there are some boulders of dark basic rock, probably a dike rock, as well as some of conglomerate derived from the Carboniferous basin about Middleborough.

Gull Island

Gull Island, which lies about three quarters of a mile east of the south point of Penikese Island, is a wave-washed shoal from which lines of boulders stretch toward Penikese. Mr. Hart noted a boulder on Gull Island 20 feet long which rose 6 feet above mean tide level. About a quarter of a mile west by south of Gull Island is a small shoal, which is dry at low water. Penikese and the adjacent isles probably once formed the summits of till-covered land having a morainal topography and representing frontal deposits laid down by the Wisconsin ice sheet on its retreat from the Falmouth moraine.

The Woepecket Isles

The Woepecket Isles[1] form a line of small islets and shoals that lie off the northeast side of the island of Naushon. The largest islet is at the southwest end of the group. Woepecket (also spelt Weepecket) island, as well as the two much smaller islets north of it, are rapidly being cut away by the waves, and their low, flattish drift tops, which are surrounded by low cliffs at the back of boulder-strewn beaches, give to the islands the appearance of great hats floating in the sea.

Woepecket Rock

Woepecket Rock is on a shoal at the east end of the group. The coast charts show a bank, with 26 and 30 feet of water, separated from the shoal on the west by depths of 47 feet at mean low water. What may be traces of a line of retreatal moraine, now shoals, dot the borders of the Bay off Quamquisset Harbor, off Gunning Point, at Gifford's Ledge, and thence northward to Southwest Ledge, off Scraggy Neck, near Cataumet. Soundings fail to reveal evidence of a submarine ridge west of the Woepecket Isles toward Penikese, but opposite the north entrance to Quicks Hole three small shoals, the largest of which is marked by "Lone Rock," may indicate the extension of the moraine.

West of Penikese Island a line of shoals on which the water ranges in depth from 23 to 29 feet extends southeastward over a bottom whose soundings run from 32 to 135 feet. This line of shoals would join the northwest corner of Nashawena if it were extended so far. It lies about two miles south of Penikese in the meridian of that island, and it is therefore probably earlier than any retreatal moraine on that island. Numerous retreatal morainal ridges no doubt occur in this area.

RIBBON REEF

Ribbon Reef and another small shoal that lies west by north of the northwest corner of Cuttyhunk suggest other morainal lines, which cannot, however, be traced over the sea floor.

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[1] See Chart No. 249, Buzzards Bay, U. S. Coast and Geodetic Survey, May, 1913.

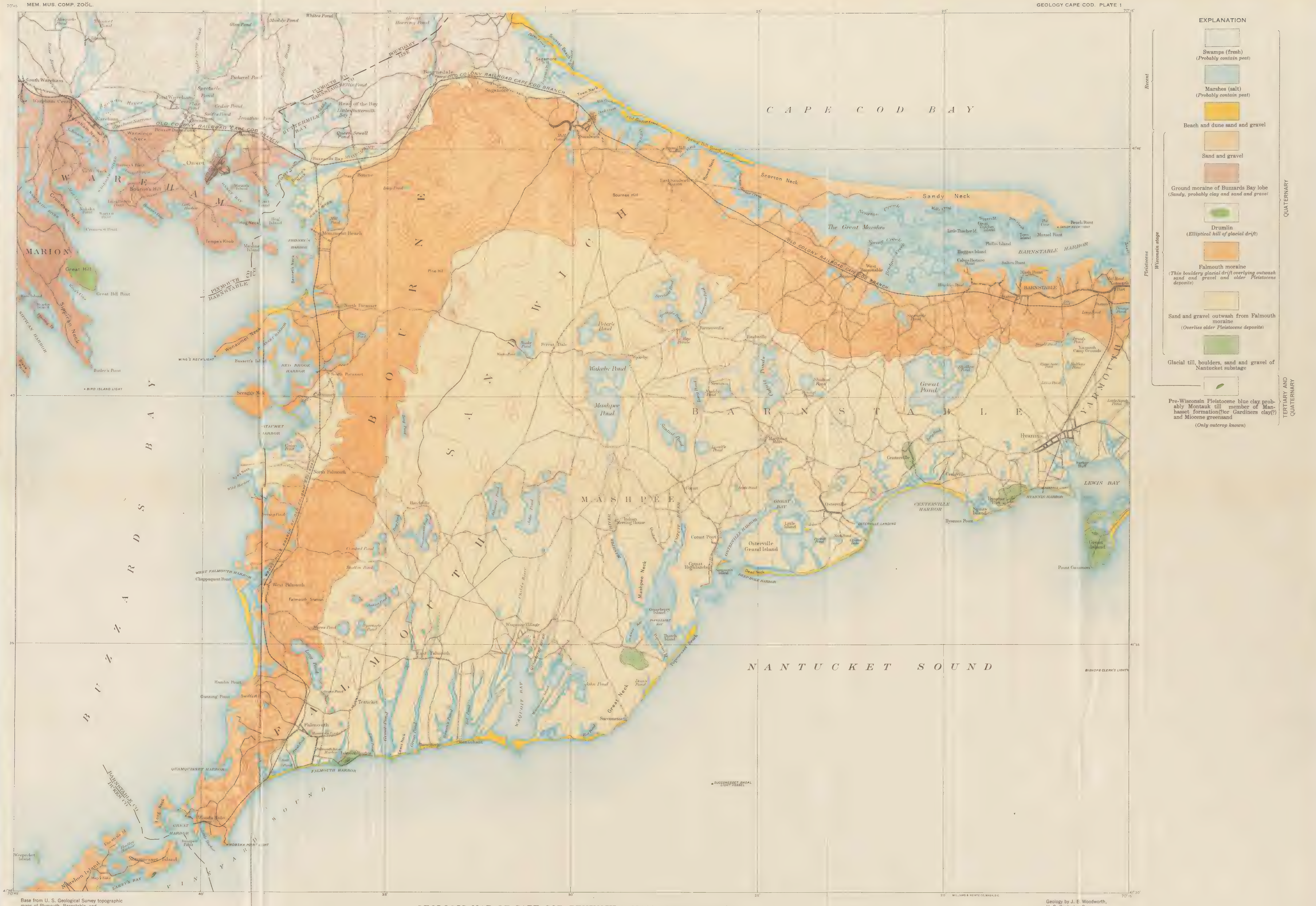
EXPLANATION OF THE PLATES

PLATE 1

PLATE 1

Geologic map of Cap Cod, western half

Base from United States Geological Survey topographic maps of Plymouth, Barnstable, and Falmouth quadrangles. Geology by J. B. Woodworth, United States Geological Survey, Gilbert Hart, field assistant, 1916. Drafting and editing supervised by the United States Geological Survey.



EXPLANATION

Recent		Swamps (fresh) *(Probably contain peat)*	QUATERNARY
		Marshes (salt) *(Probably contain peat)*	
		Beach and dune sand and gravel	
Pleistocene	Wisconsin stage	Sand and gravel	
		Ground moraine of Buzzards Bay lobe *(Sandy, probably clay and sand and gravel)*	
		Drumlin *(Elliptical hill of glacial drift)*	
		Falmouth moraine *(Thin bouldery glacial drift overlying outwash sand and gravel and older Pleistocene deposits)*	
		Sand and gravel outwash from Falmouth moraine *(Overlies older Pleistocene deposits)*	
		Glacial till, boulders, sand and gravel of Nantucket substage	
		Pre-Wisconsin Pleistocene blue clay, probably Montauk till member of Manhasset formation(?) or Gardiners clay(?) and Miocene greensand *(Only outcrop known)*	TERTIARY AND QUATERNARY

Base from U. S. Geological Survey topographic maps of Plymouth, Barnstable, and Falmouth quadrangles, reprinted from earlier editions without revision

GEOLOGIC MAP OF CAPE COD PENINSULA, MASS. (WEST HALF)

Scale $\frac{1}{62500}$

Miles

Kilometers

Contour interval 20 feet

Datum is mean sea level

Geology by J. B. Woodworth,
U. S. Geological Survey,
Gilbert Hart, field assistant, 1916

PLATE 8

PLATE 2

Geologic map of Cape Cod, eastern half

Base from U. S. Geological Survey topographic maps of Provincetown, Wellfleet, Yarmouth and Chatham quadrangles. Geology by J. B. Woodworth, United States Geological Survey, 1916. Drafting and editing supervised by the United States Geological Survey.

EXPLANATION
Swamps (fresh)
(Probably contain peat)
Marshes (salt)
(Probably contain peat)
Beach and dune sand and gravel
(Mainly as mapped in 1887)
Recent
Sand and gravel, thin, of the North Truro plain, overlying eroded surface of older Pleistocene sand, gravel, and Gardiners (?) clay
Sand and gravel and scattered boulders of the Wellfleet plain, overlying eroded surface of older Pleistocene sand, gravel, and Gardiners (?) clay
Outwash sand and gravel of the Eastham plain, with kame belt on the south
(Deposited by streams flowing westward from an ice front on the east)
Falmouth moraine
(Thin bouldery glacial drift overlying outwash sand and gravel and older Pleistocene deposits)
Sand and gravel outwash from Falmouth moraine overlying older Pleistocene deposits
Sand and gravel of unknown stratigraphic relations
Wisconsin stage
Sand and gravel of Chatham plain, partly of Nantucket substage of Wisconsin but chiefly pre-Wisconsin deposits
(These and similar beds beneath intervening swamps and ponds prevented the remnants of ice of Nantucket substage from being covered by outwash from the Falmouth moraine)
Gardiners (?) clay
Pre-Wisconsin
Pleistocene
QUATERNARY
PROVINCETOWN
PROVINCETOWN HARBOR
TRURO
WELLFLEET
WELLFLEET HARBOR
EASTHAM
ORLEANS
BREWSTER
HARWICH
DENNIS
YARMOUTH
CHATHAM
PLEASANT BAY
MONOMOY ISLAND
CAPE COD BAY
ATLANTIC OCEAN
NANTUCKET SOUND
70°15'
10'
5'
70°00'
69°55'
WILLIAMS & HEINTZ CO. WASH. D.C.

Base from U. S. Geological Survey topographic maps of Provincetown, Wellfleet, Yarmouth, and Chatham quadrangles, reprinted from earlier editions without revision

GEOLOGIC MAP OF CAPE COD PENINSULA, MASS. (EAST HALF)

Scale $\frac{1}{62500}$

Miles

Kilometers

Contour interval 20 feet.

Datum is mean sea level.

Geology by J. B. Woodworth,
U. S. Geological Survey, 1916

PLATE 3

PLATE **3**

Outline map of Elizabeth Islands.

Shorelines from U. S. Coast and Geodetic Survey Sheet No. 1210, with soundings and other features omitted. Drawing and cut prepared under the supervision of the United States Geological Survey.

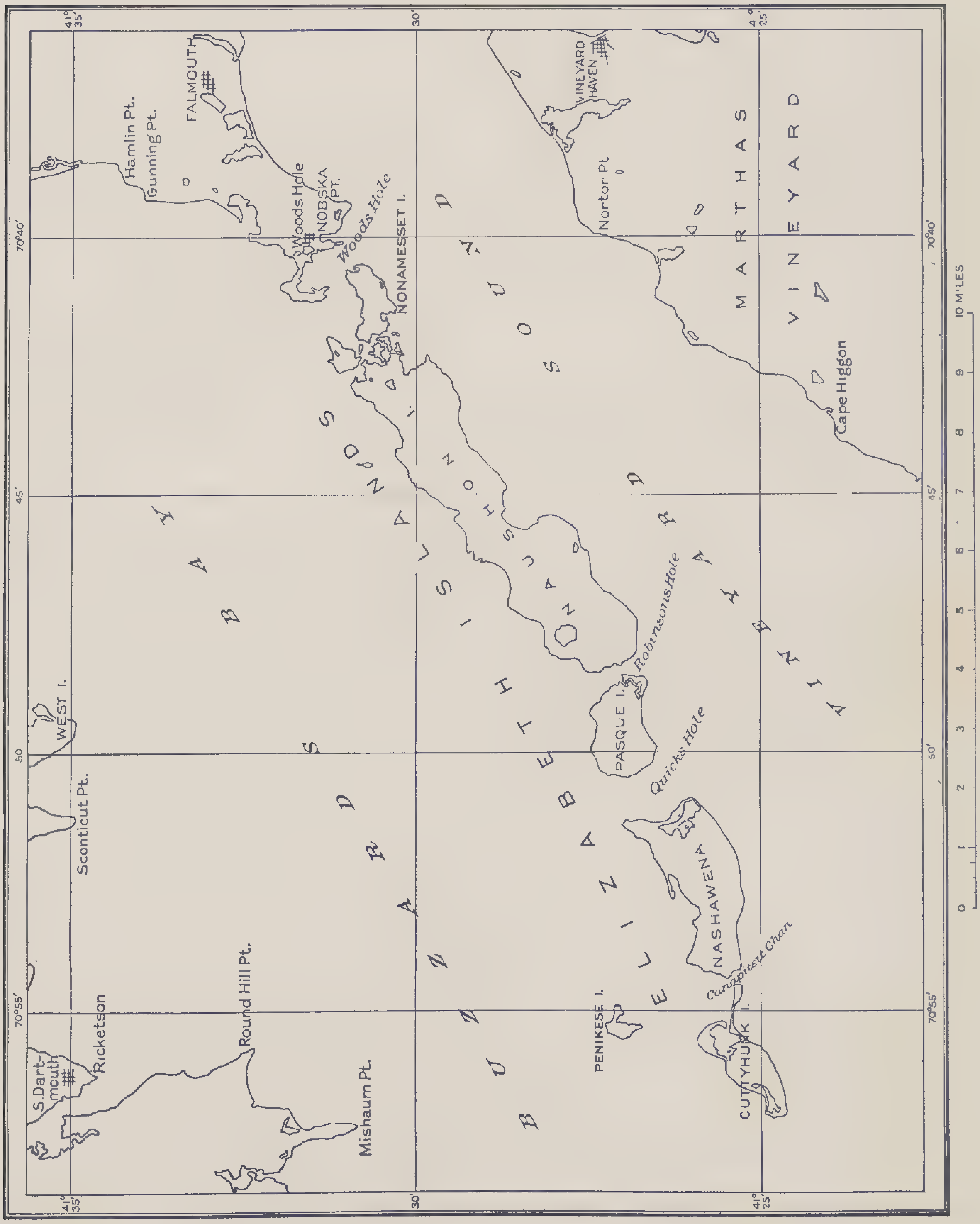
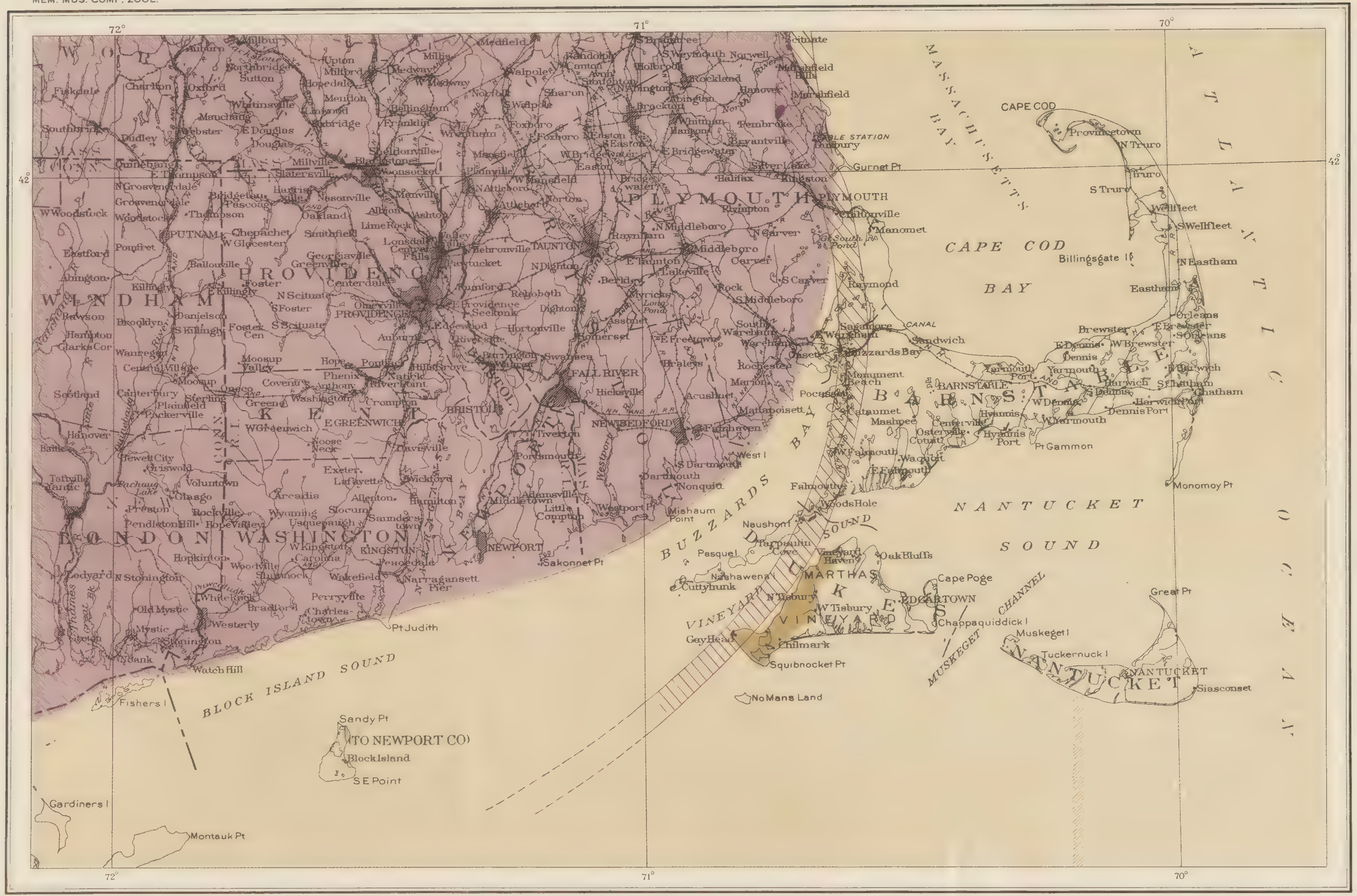

BUZZARDS BAY
ELIZABETH ISLANDS
VINEYARD SOUND
MARTHAS VINEYARD
FALMOUTH
Hamlin Pt.
Gunning Pt.
Woods Hole
NOBSKA PT.
Woods Hole
NONAMESSET I.
NAUSHON I.
VINEYARD HAVEN
Norton Pt.
Cape Higgon
Robinsons Hole
PASQUE I.
Quicks Hole
NASHAWENA
Canapitset Chan
CUTTYHUNK I.
PENIKESE I.
WEST I.
Sconticut Pt.
Ricketson
Round Hill Pt.
Mishaum Pt.
S. Dartmouth
41° 35'
30'
41° 25'
70°40'
45'
50'
70°55'
0 1 2 3 4 5 6 7 8 9 10 MILES

PLATE 4

PLATE 4

Map of coastal plain formations of southeastern Massachusetts, Rhode Island, and eastern Connecticut.

Base from United States Geological Survey. Geology by J. B. Woodworth, United States Geological Survey, 1915–1916. Drafting and editing supervised by the United States Geological Survey.



Base from U. S. Geological Survey
1:500,000 scale map

WILLIAMS & HEINTZ CO. WASH. D.C.

MAP OF COASTAL PLAIN FORMATIONS OF SOUTHEASTERN MASSACHUSETTS, RHODE ISLAND, AND EASTERN CONNECTICUT

Geology by J. B. Woodworth,
U.S. Geological Survey, 1915–1916

EXPLANATION

Sign	Explanation
●	Miocene greensand (only known outcrops shown).
▨	Area in which Cretaceous sediments may be buried.
■	Upper Cretaceous infolded with Miocene and older Pleistocene deposits.
■	Paleozoic and older rocks.
▨	Approximate zone of Miocene deposits.

Scale $\frac{1}{500{,}000}$

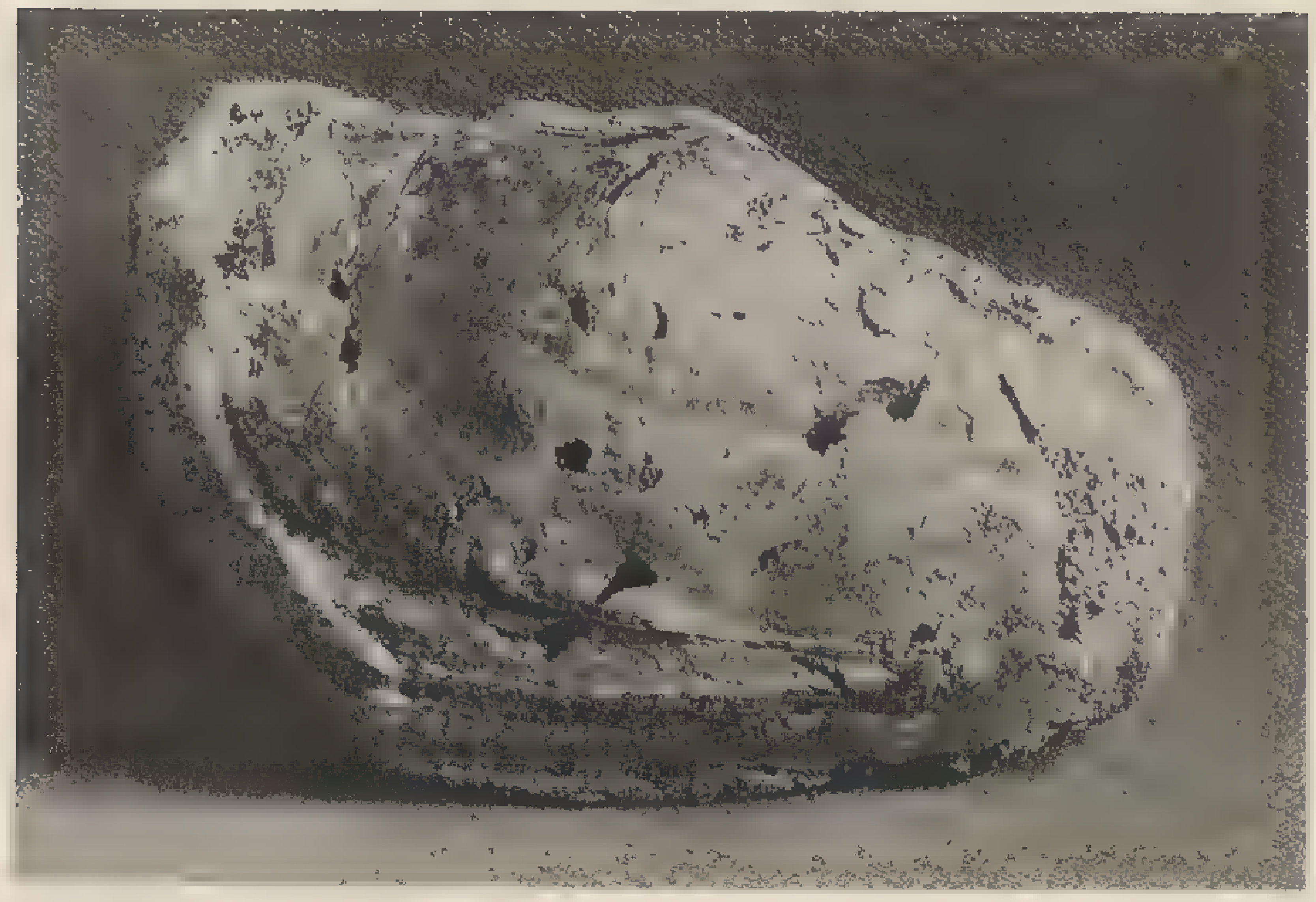
0 10 20 30 Miles

PLATE 5

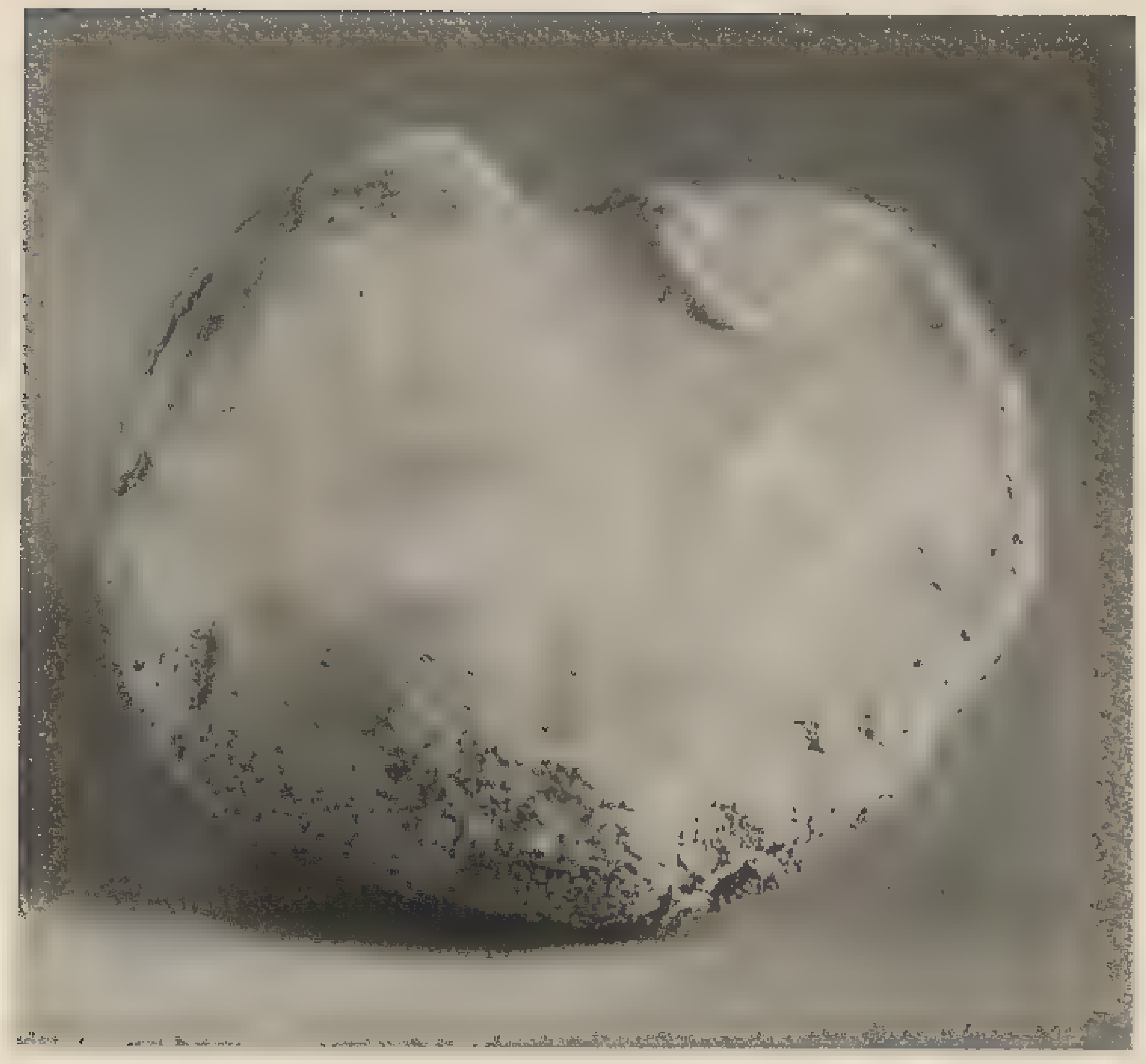
PLATE 5

Fossil mollusks from the Miocene greensand.

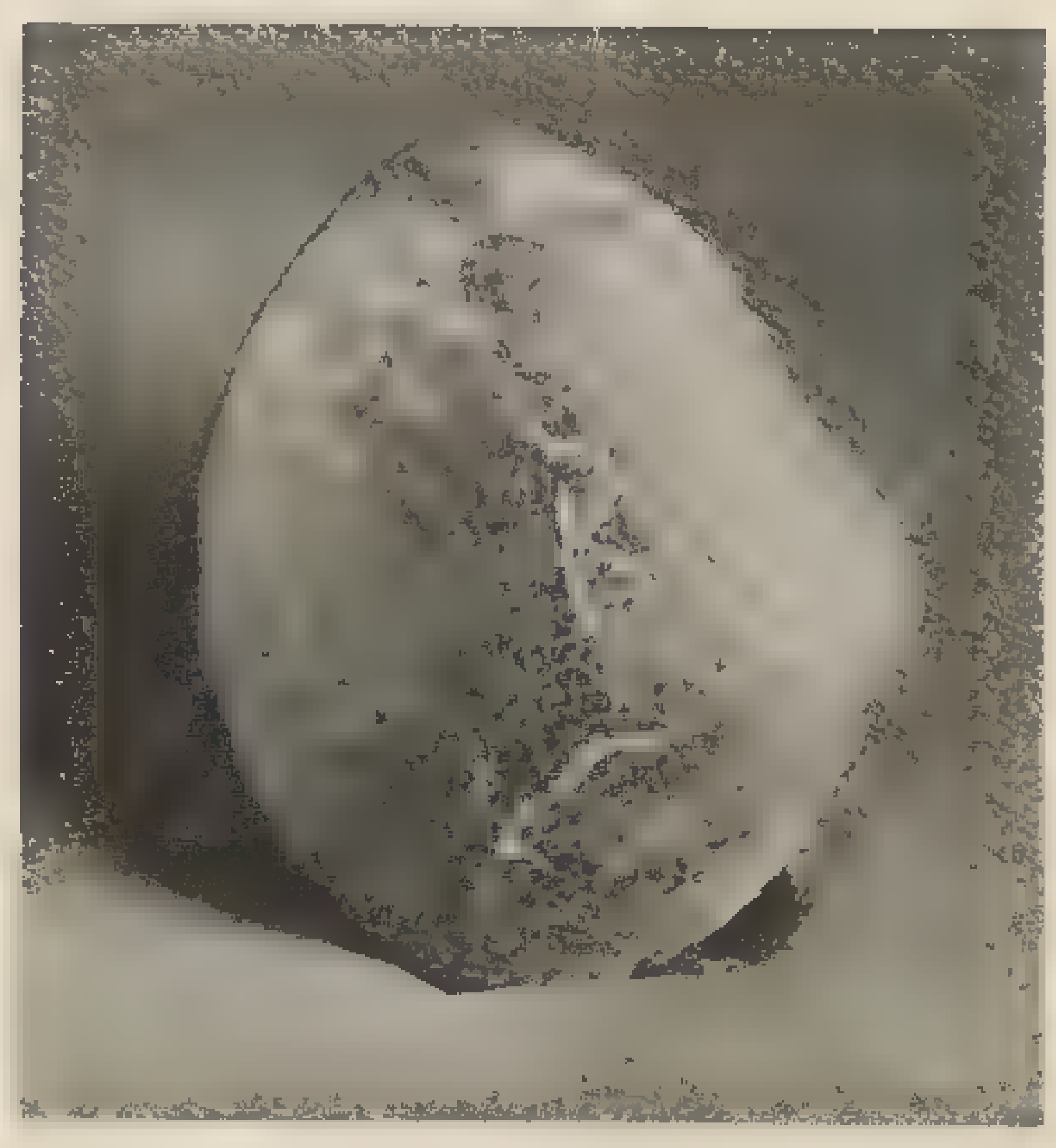
Fig. 1. *Panopea* sp. Daniel Webster estate, Marshfield, Mass.
Fig. 2. *Venus* sp. Marshfield, Mass.
Fig. 3. *Macoma lyalli* Dall. Gay Head, Mass.



1



2



3

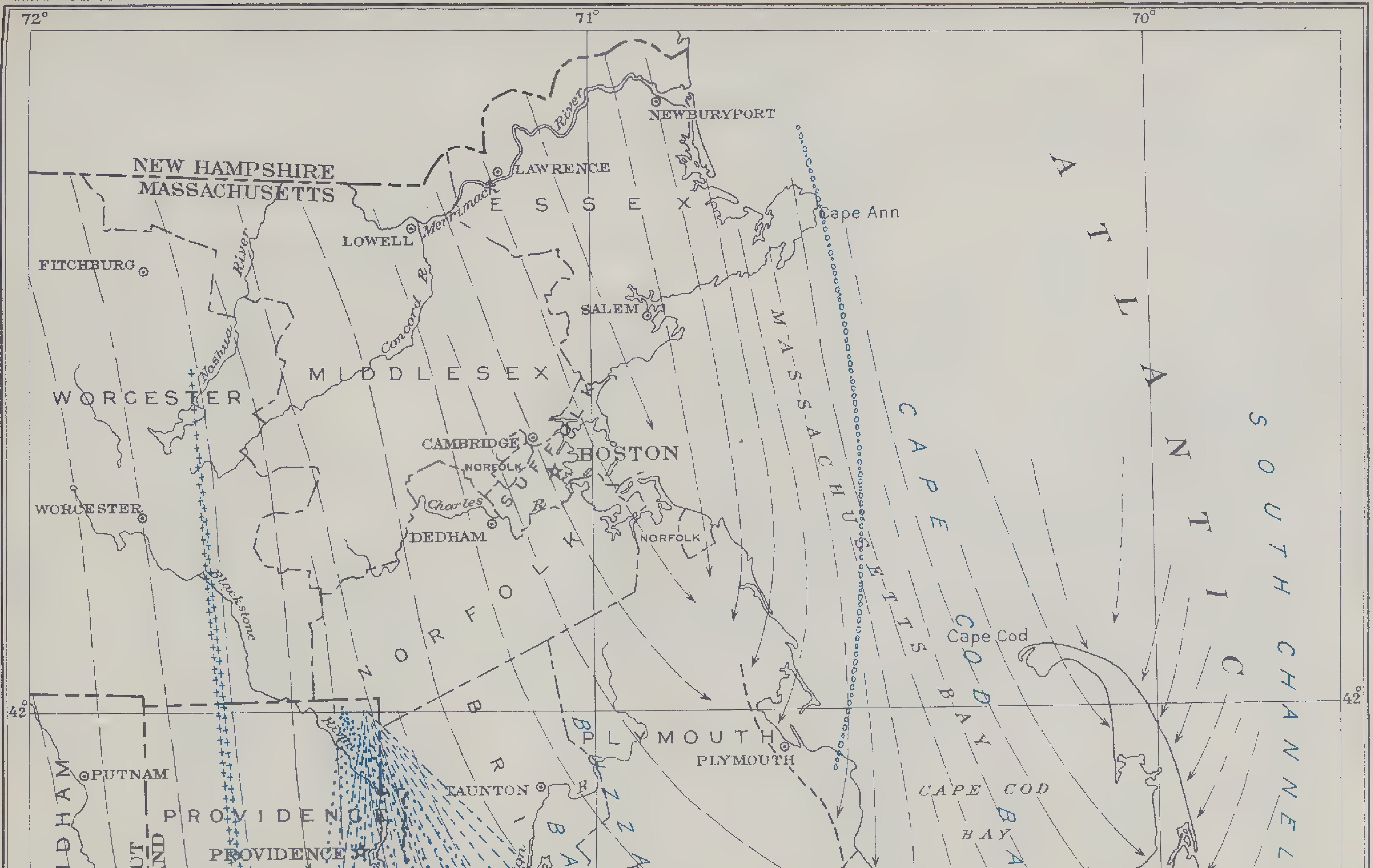
HELIOTYPE CO. BOSTON

PLATE 6

PLATE 6

Map of eastern Massachusetts and Rhode Island, showing extent, directions of movement, terminal moraines, and boulder fans of ice sheet of Wisconsin stage of glaciation.

Drafting and editing supervised by the United States Geological Survey.

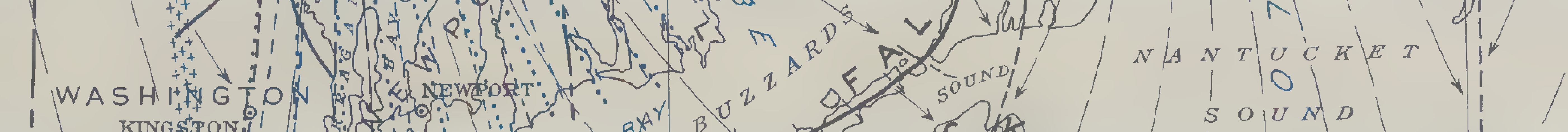


MAP OF EASTERN MASSACHUSETTS AND RHODE ISLAND SHOWING EXTENT, DIRECTIONS OF MOVEMENT, TERMINAL MORAINES AND BOULDER FANS OF ICE SHEET OF WISCONSIN STAGE OF GLACIATION.

By J. B. Woodworth.

10	0	10	20	30 Miles

10	0	10	20	30	40 Kilometers



Terminal moraine.	Direction of ice movement. (Generalized).	General drift of chiastolite-bearing glacial pebbles and boulders from Georges Hill to Block Island.	Peridotite boulder fan spreading from Mine Hill to Gay Head and Block Island.	Distribution of ice-borne agate pebbles probably derived near Diamond Hill.	Probable trail of ice-borne porphyritic dike rock fragments found in drift at Plymouth, Mass.

PLATE **7**

PLATE 7

Map of Cape Cod, Mass., showing an old cross-channel south of Eastham.

Reproduced from a copy of part of "A portion of a Map of New England in The Public Record Office, London, England. Copied for Charles Hervey Townshend, Esq. of 'Raynham,' New Haven, Conn., U. S. A., by L. M. Byrne, April, 1887," as published in U. S. Coast and Geodetic Survey Report for 1890, Plate 71.

"Captain Townshend is of opinion from evidence afforded by the chart itself, and by the copious notes it contains relative to the coasts, shoals, and passages embraced within its limits, that it was constructed by a hydrographical survey party, composed of British naval officers, between the years 1715 and 1720. There are, however, some indications that parts of it had an origin from 20 to 30 years earlier."

The officer referred to in the note, opposite the old passage way through Cape Cod, "was probably Captain Cyprian Southack, a Boston pilot, who commanded a ship in the expedition against Quebec, 1690."

Drafting and editing supervised by the United States Geological Survey.

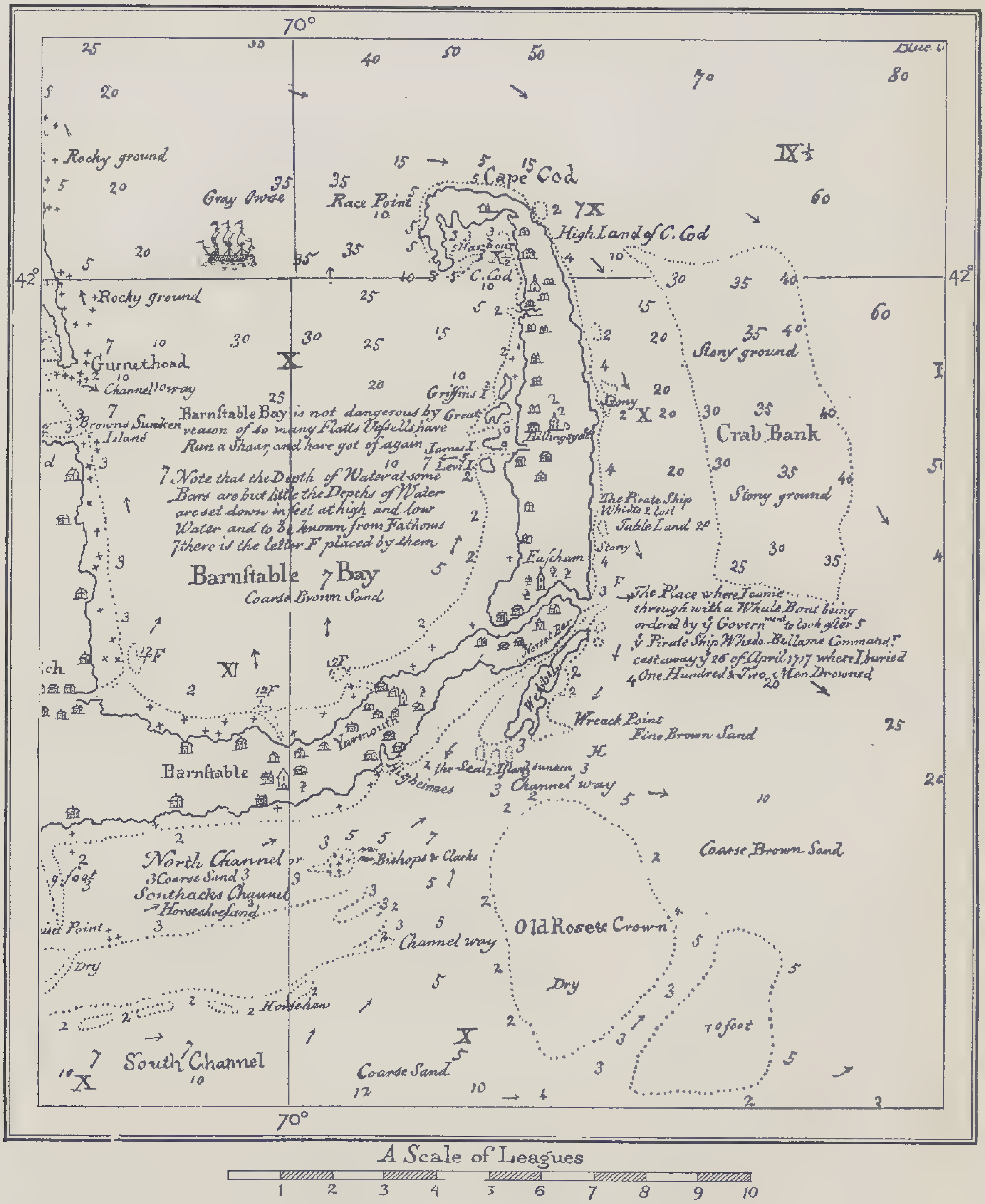
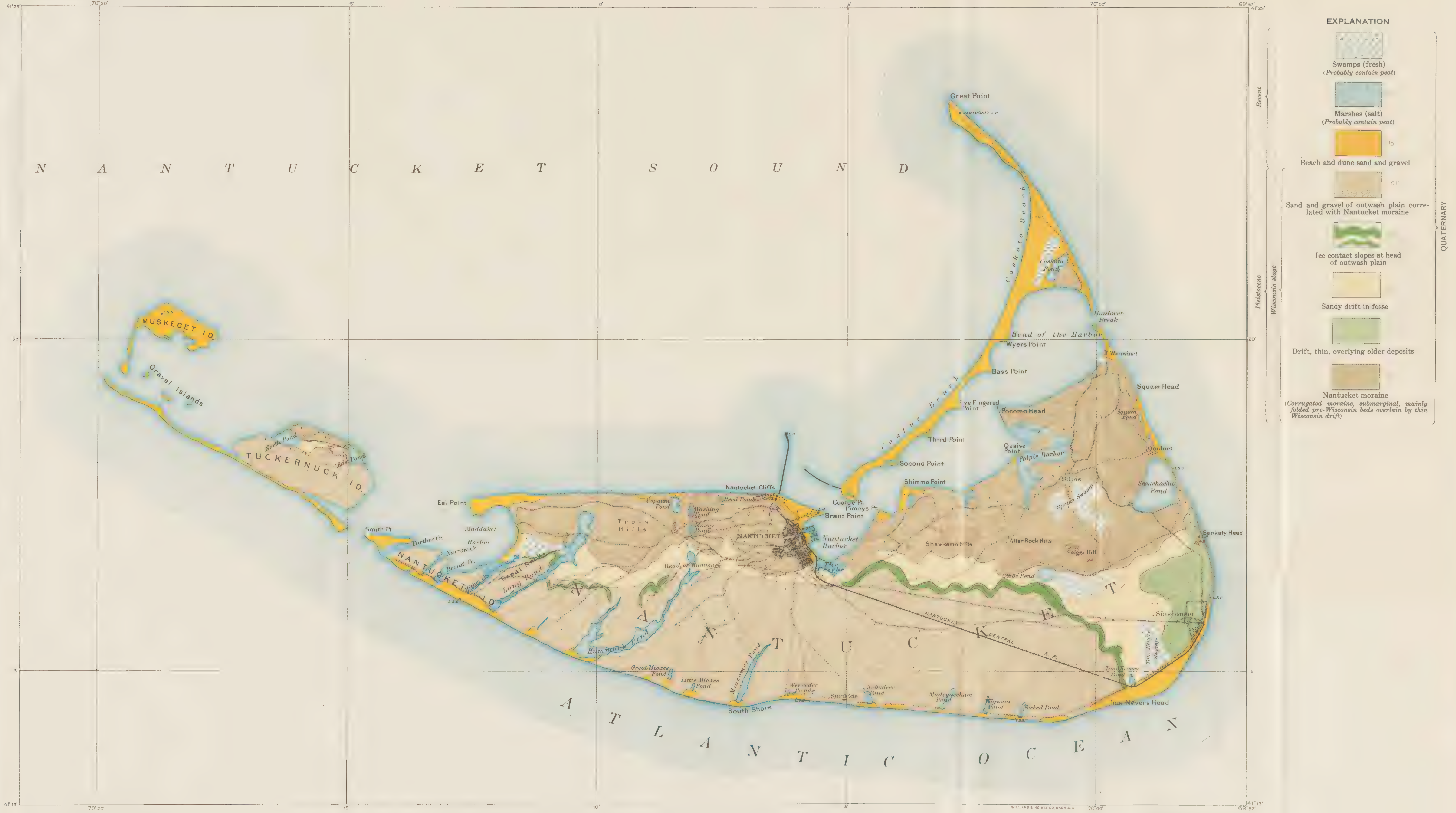

70°
42°
Cape Cod
Race Point
Gray Owse
Rocky ground
Harbour
C. Cod
High Land of C. Cod
Gurnethead
Channel way
Browns Sunken Island
Griffins I.
Great I.
James I.
Levi I.
Billingsgate
Barnstable Bay is not dangerous by reason of so many Flatts Vessells have Run a Shoar, and have got of again
Note that the Depth of Water at some Bars are but little the Depths of Water are set down in feet at high and low Water and to be known from Fathoms there is the letter F placed by them
Barnstable Bay
Coarse Brown Sand
Stony ground
Crab Bank
Stony ground
The Pirate Ship Whido lost
Table Land
Stony
Eastham
The Place where I came through with a Whale Boat being ordered by ye Governmt to look after ye Pirate Ship Whido Bellame Commandr cast away ye 26 of April 1717 where I buried One Hundred & Two Men Drowned
Wreack Point
Fine Brown Sand
Nosset Bay
Yarmouth
Barnstable
the Seal Island
sunken
Channel way
Hyheimes
Bishops & Clarks
North Channel or Southacks Channel
Coarse Sand
Horseshoe Sand
Channel way
Old Rose & Crown
Dry
Coarse Brown Sand
Horseshoe
South Channel
Coarse Sand
10 foot
9 foot
Dry
Point
IX ½
X
XI
A Scale of Leagues
1
2
3
4
5
6
7
8
9
10

PLATE 8

PLATE 8

Geologic map of Nantucket, Mass.

Base from the United States Geological Survey topographic maps of Muskeget and Nantucket quadrangles. Geology by J. B. Woodworth, United States Geological Survey, 1915–1916. Drafting and editing supervised by the United States Geological Survey.



Base from U. S. Geological Survey topographic
maps of Muskeget and Nantucket quadrangles
reprinted from earlier editions without revision

GEOLOGIC MAP OF NANTUCKET, MASS.

Scale $\frac{1}{62500}$

Contour interval 20 feet.

Datum is mean sea level.

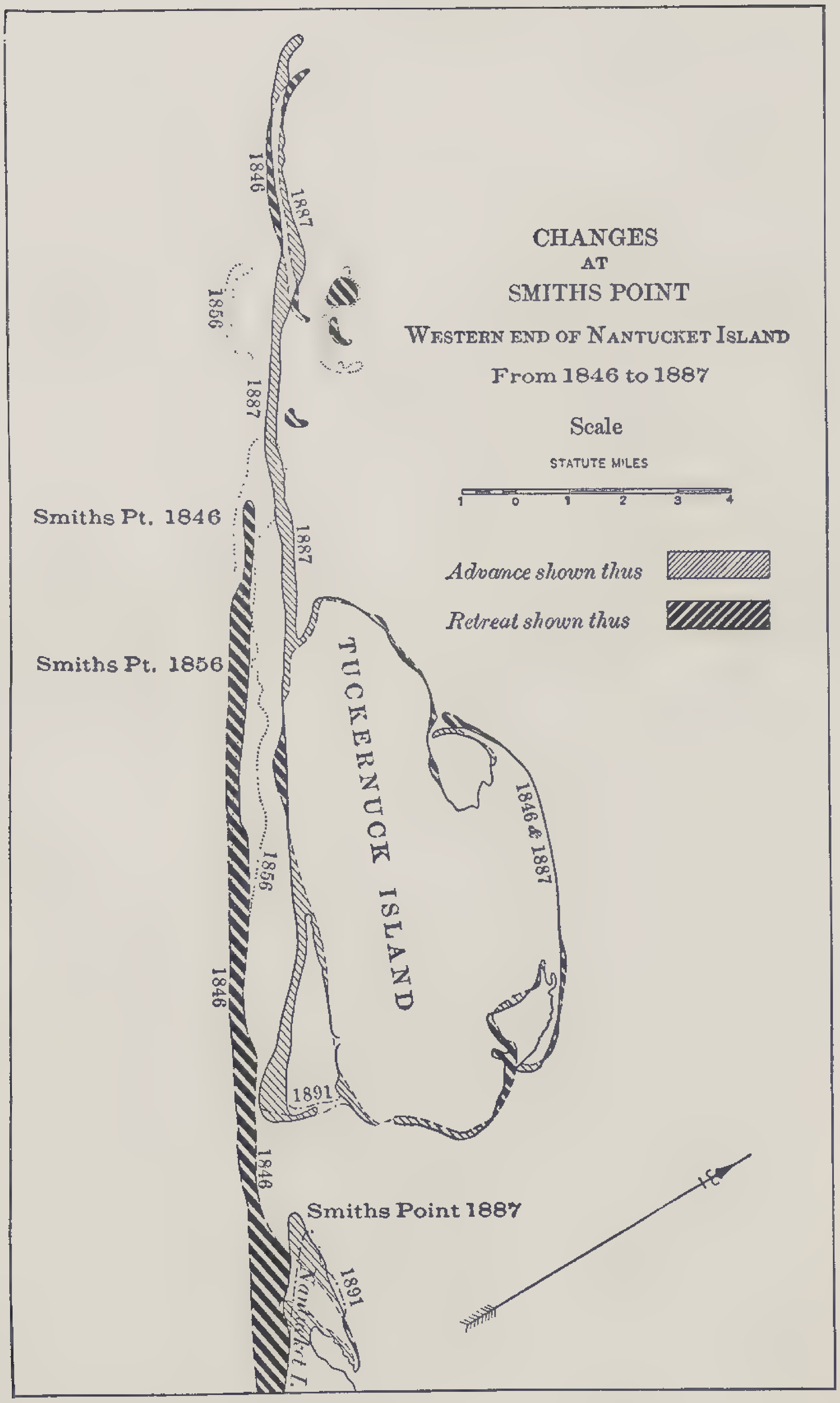
Geology by J. B. Woodworth,
U. S. Geological Survey, 1915–1916

PLATE 9

PLATE 9

Map showing changes at Smiths Point, Nantucket Island, from 1846–1887.

Reproduced from a report by Henry L. Marindin, United States Coast and Geodetic Survey, Report for 1892, Pt. 2; App. No. 6, Plate **27**, *op. cit.*, p. 248, 1893. Drawing and cut prepared under the supervision of the United States Geological Survey.



CHANGES AT SMITHS POINT
WESTERN END OF NANTUCKET ISLAND
From 1846 to 1887

PLATE **10**

PLATE **10**

Views of the eastern coast of Nantucket in 1916

Fig. 1. Gullied cliff near Siasconset, looking north.
Fig. 2. Pebbly clays at Wauwinet. (See p. 169).

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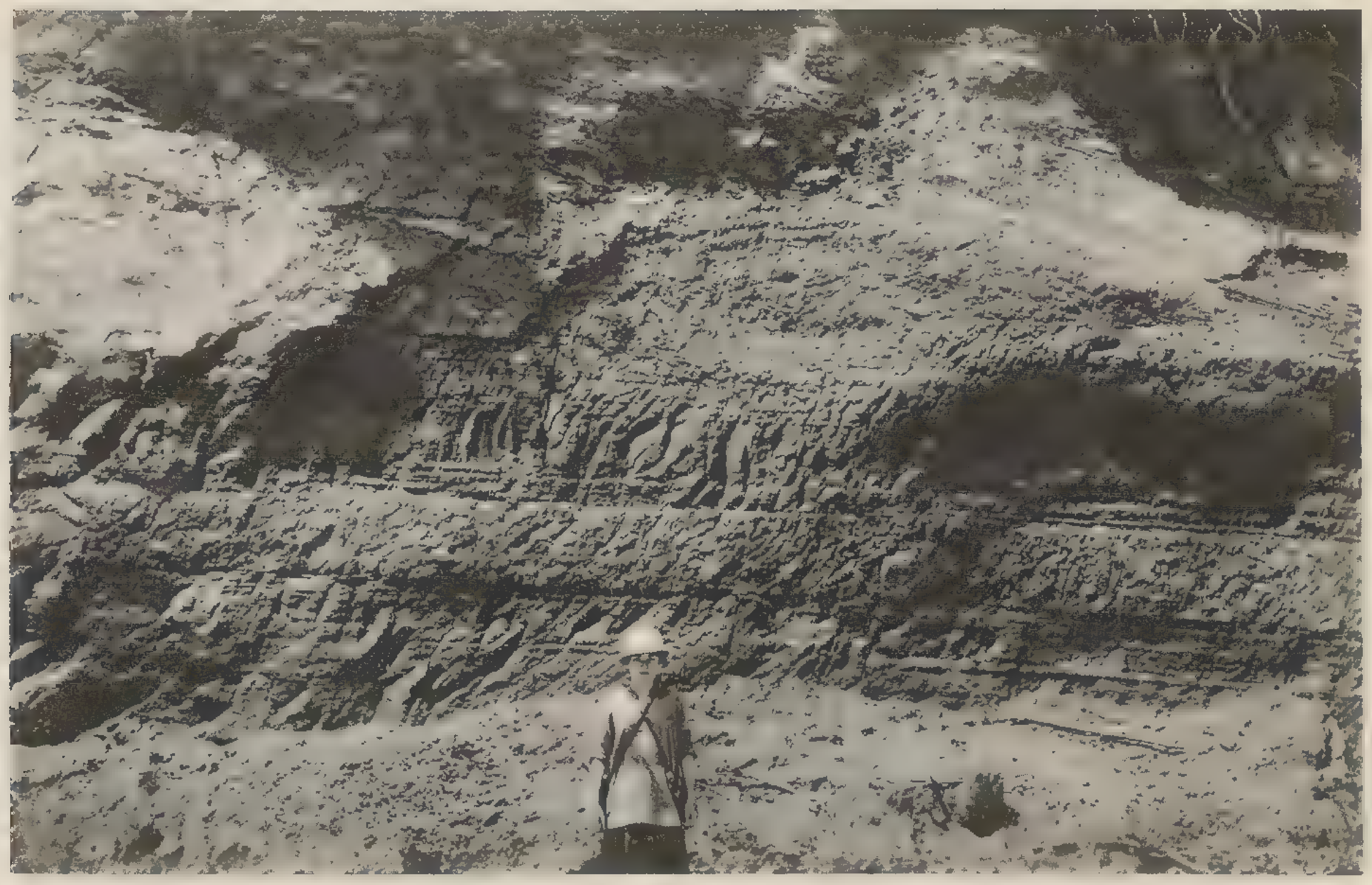

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HELIOTYPE CO. BOSTON

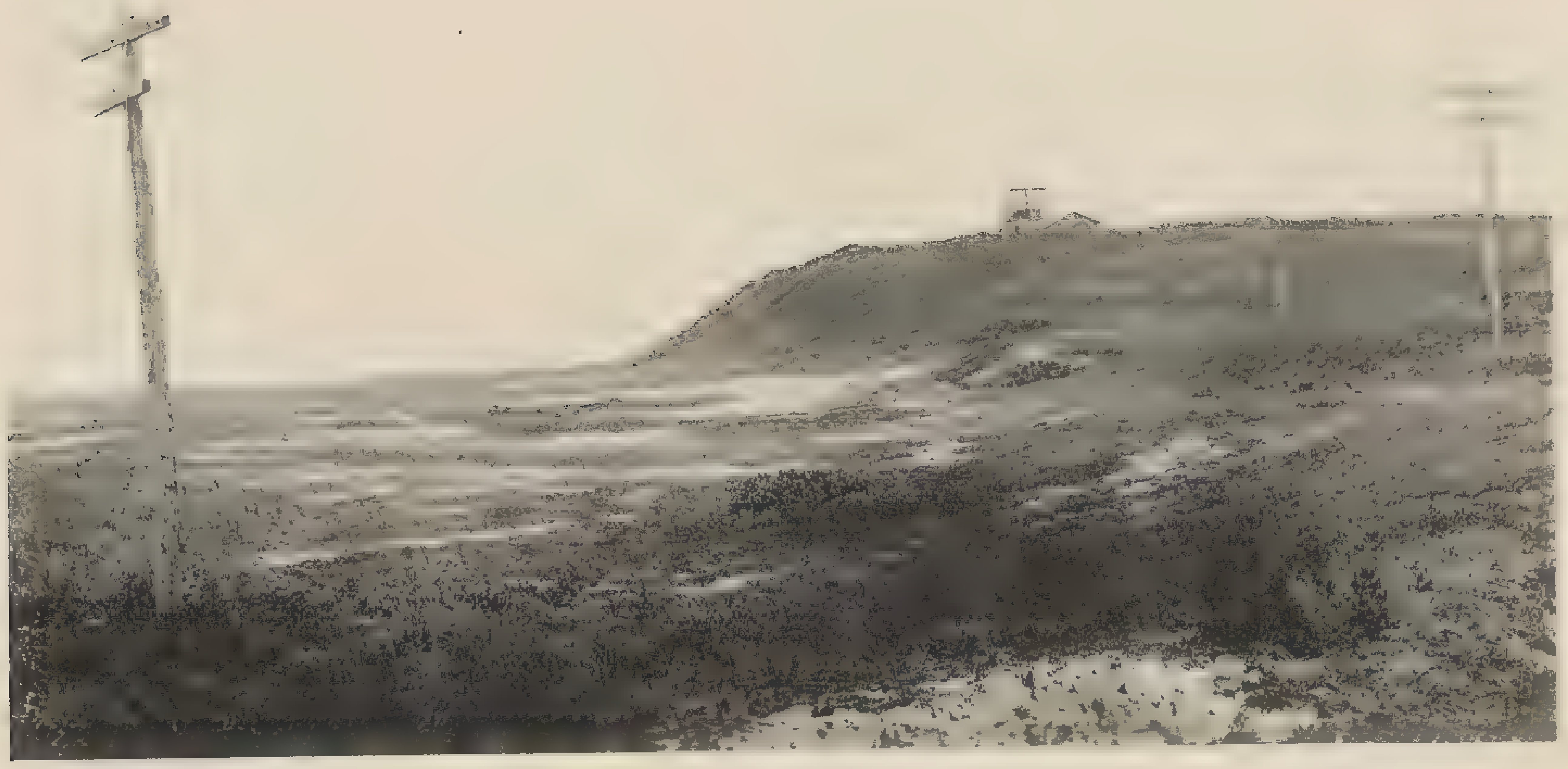
PLATE 11

PLATE **11**

Views of the surface of Nantucket

Fig. 1. Southern side. Sea cliff, Tom Never's Head. Ice-contact slope marking the front of the ice sheet on the right of the cliff.

Fig. 2. West of town of Nantucket looking south. Corrugated moraine enclosing swamp.



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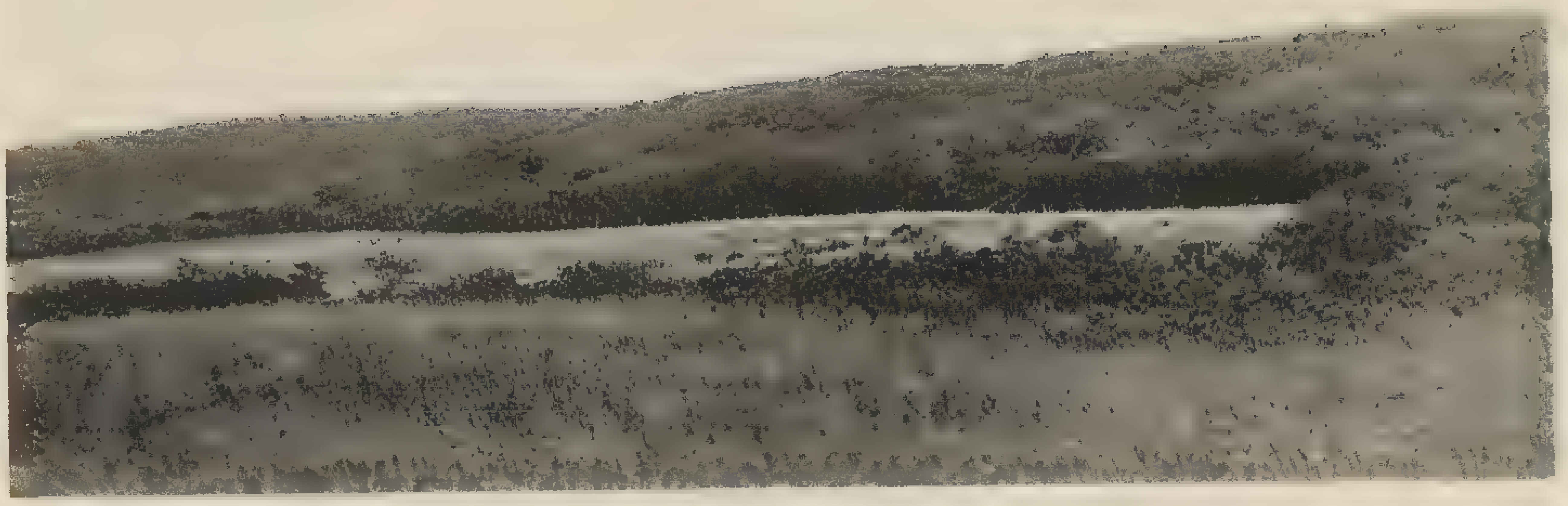

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HELIOTYPE CO. BOSTON

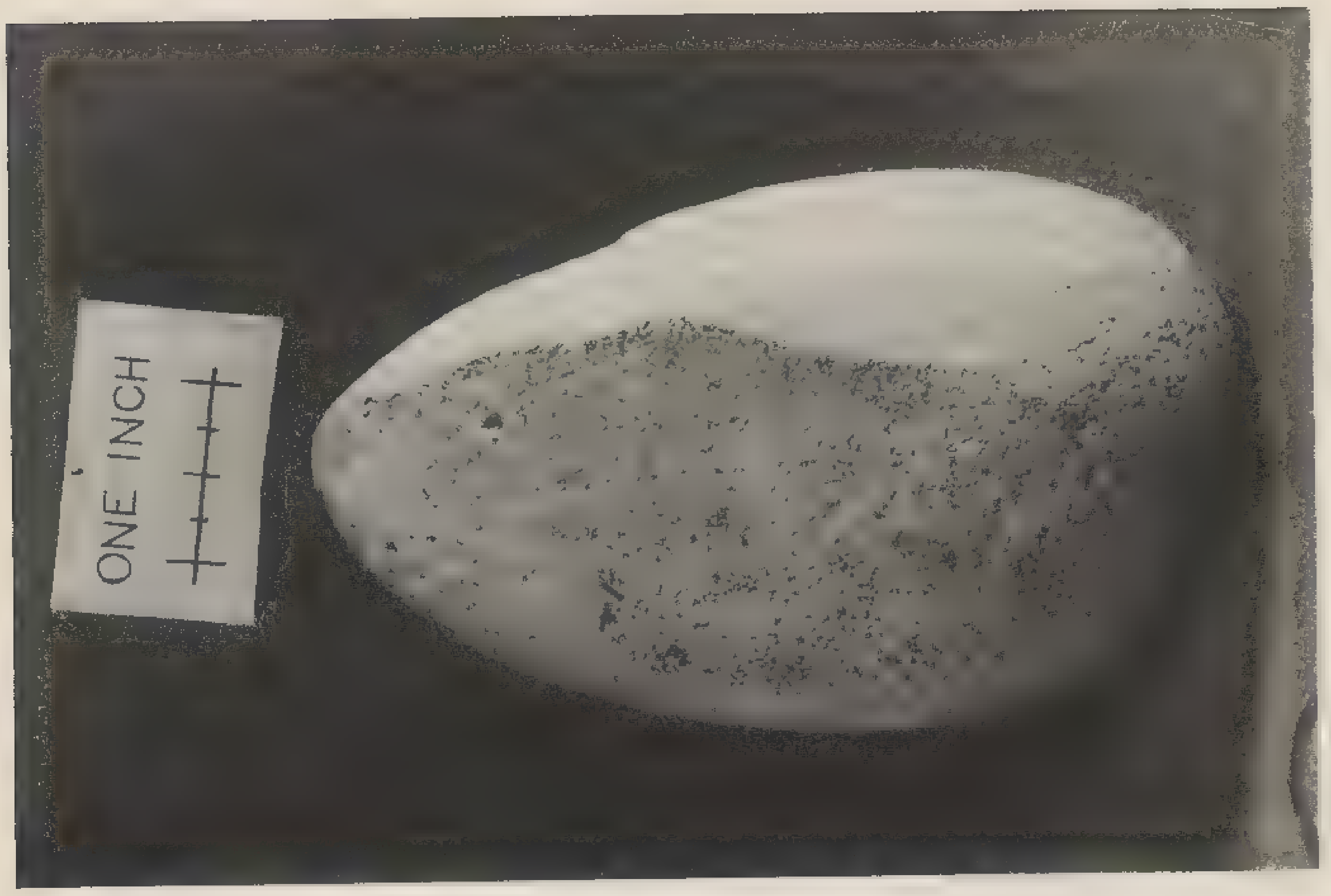
PLATE 12

PLATE 12

Pebbles and stones carved by sand blast.

Fig. 1. Sand-blasted glacial pebble (glyptolith), from the surface of a wind-blown tract.

Fig. 2. Sand-blasted glacial erratic (glypolith) of the three-edged type, from cliffs, north side of Nantucket. The under side shows glacial striation unaffected by subsequent wear.



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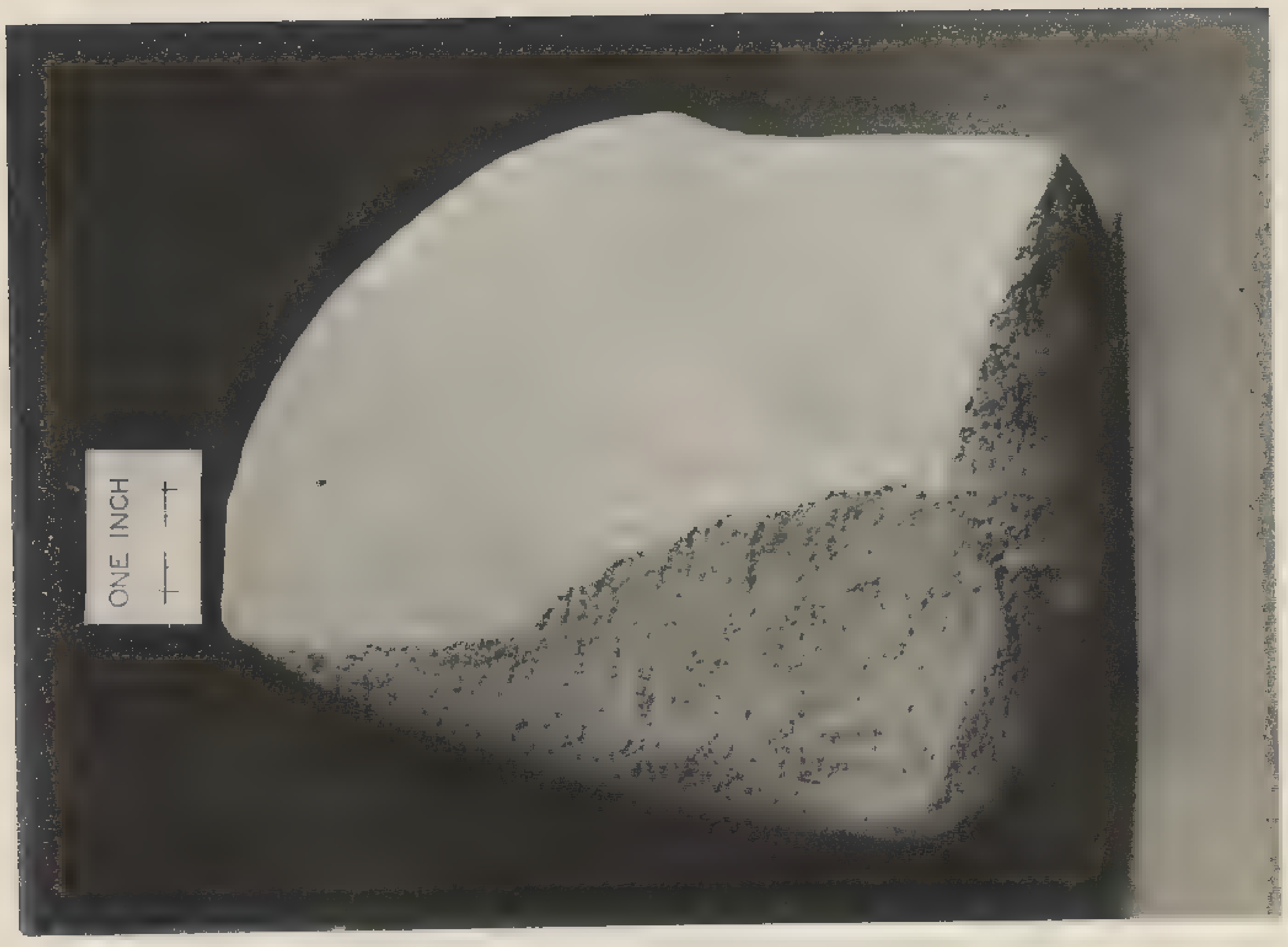

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HELIOTYPE CO. BOSTON

PLATE 13

PLATE 13

Geologic map of Marthas Vineyard and of part of Elizabeth Islands and No Mans Land, Mass.

Base from the United States Geological Survey topographic maps of Gay Head and Marthas Vineyard quadrangles. Geology by J. B. Woodworth, United States Geological Survey, assisted by E. Wigglesworth and Gilbert Hart, 1915–1916. Drafting and editing under the supervision of the United States Geological Survey.

EXPLANATION
Swamps (fresh)
Marshes (salt)
Beach and dune sand and gravel
Falmouth moraine
(Thin bouldery glacial drift overlying older Pleistocene deposits, mostly sand and gravel)
Nantucket moraine
(Corrugated moraine, mainly of folded pre-Wisconsin clay, sand, gravel, and glacial till overlain by thin bouldery Wisconsin drift)
Outwash sand and gravel correlated with Nantucket moraine
Pre-Wisconsin Pleistocene deposits, including folded and faulted glacial tills, boulders, sand, gravel, and Gardiners clay (marine)
Older Pleistocene, Miocene, and Upper Cretaceous deposits
(Includes folded and faulted glacial till, boulders, sand, and gravel overlying Aquinnah conglomerate (earliest Pleistocene); Miocene greensand; Upper Cretaceous white clay and gravel (partly marine?) and variegated clays and lignite)
Recent
Pleistocene
Wisconsin stage
QUATERNARY
CRETACEOUS, TERTIARY, AND QUATERNARY
BUZZARDS BAY
ELIZABETH ISLANDS
VINEYARD SOUND
ATLANTIC OCEAN
MARTHAS VINEYARD
Naushon Island
Pasque Island
Nashawena Island
Cuttyhunk Island
Penikese Id.
Gull Id
Tarpaulin Cove Light
Gay Head
Chilmark
West Tisbury
Tisbury
Edgartown
Cottage City
Vineyard Haven
Oak Bluffs
Chappaquiddick Id.
Cape Poge
Edgartown Harbor
Katama Bay
Tisbury Great Pond
Edgartown Great Pond
Menemsha Pond
Squibnocket Pond
Gay Head Light
NO MANS LAND
WILLIAMS & HEINTZ CO. WASH. D.C.

Base from U. S. Geological Survey topographic
maps of Gay Head and Marthas Vineyard
quadrangles, reprinted from earlier
editions without revision

GEOLOGIC MAP OF MARTHAS VINEYARD AND OF PART OF ELIZABETH ISLANDS AND NO MANS LAND, MASS.

Scale $\frac{1}{62500}$

Contour interval 20 feet

Datum is mean sea level

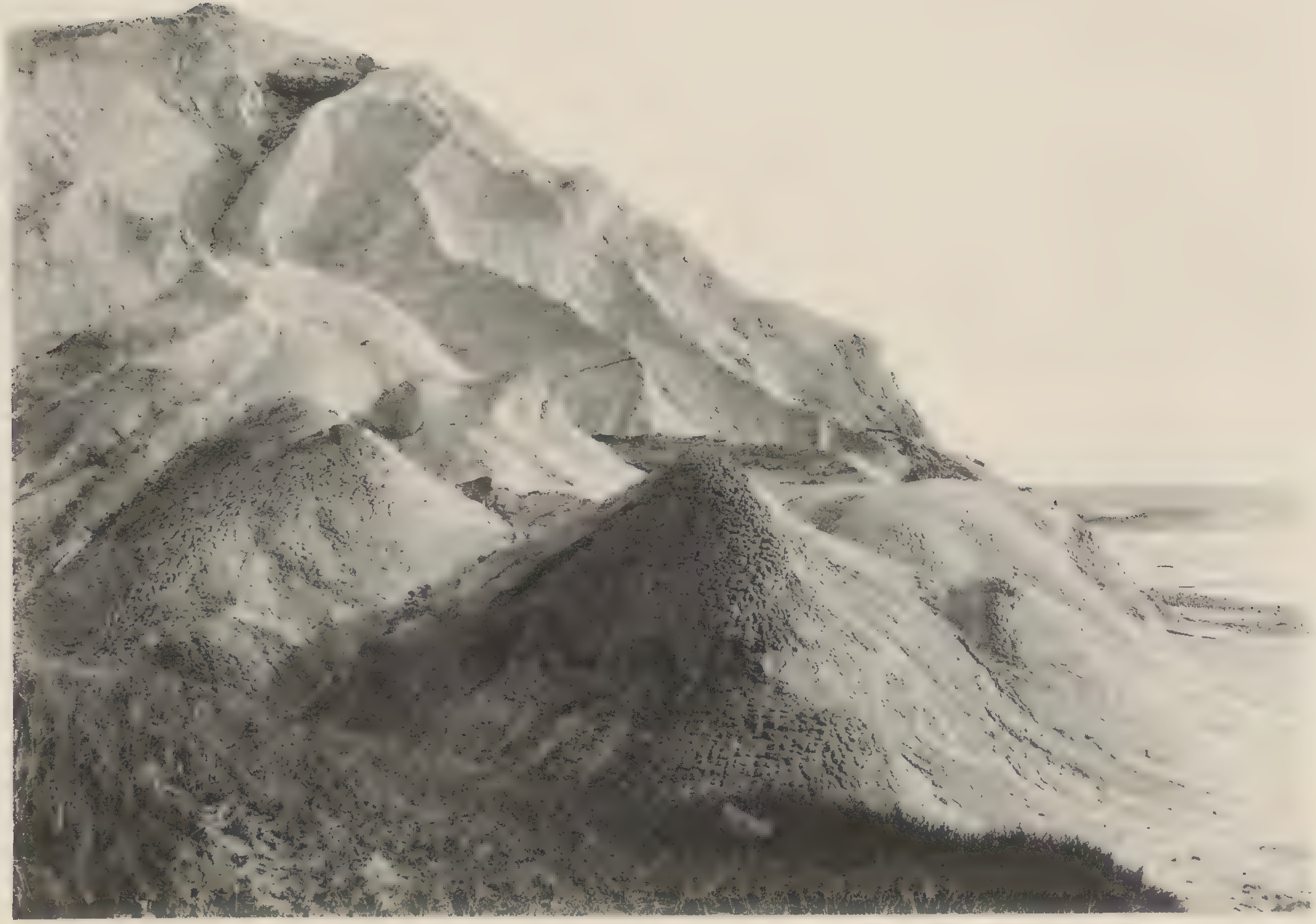
Geology by J. B. Woodworth,
U. S. Geological Survey, assisted by
E. Wigglesworth and Gilbert Hart, 1915-1916

PLATE **14**

HELIOTYPE CO. BOSTON

PLATE 14

Gay Head Cliffs, south of Devils Den, Marthas Vineyard. Photograph, April, 1894, by Philip P. Sharples.



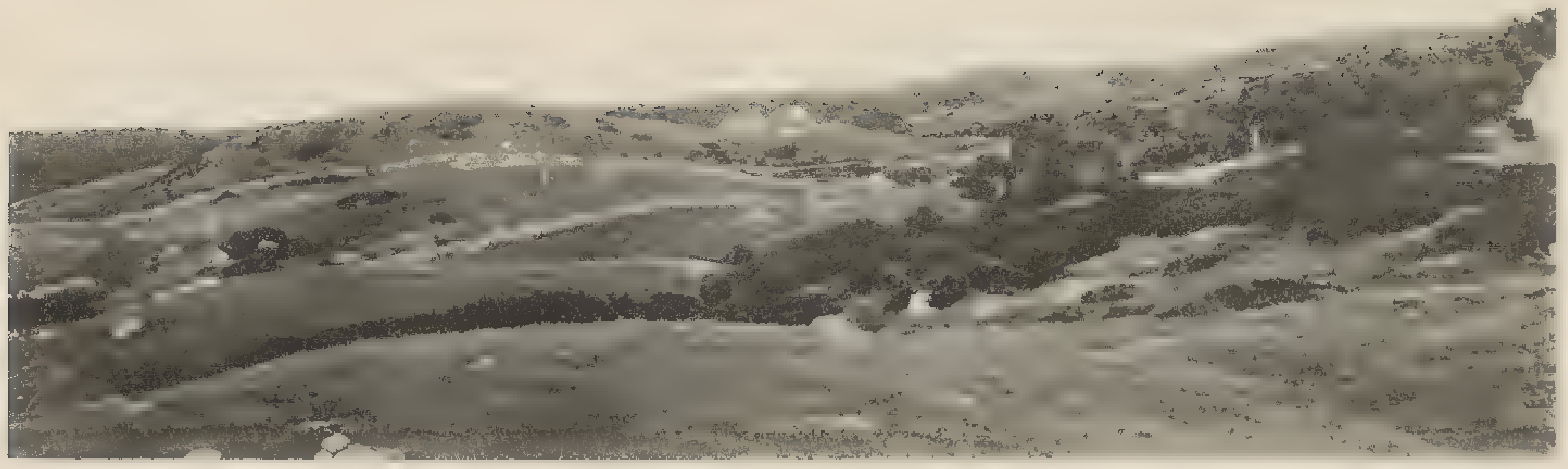
HELIOTYPE CO. BOSTON

PLATE **15**

PLATE 15

Views of the glacial deposits of Marthas Vineyard

Fig. 1. Morainal topography in West Tisbury near the Chilmark line.
Fig. 2. The outwash plain with the western moraine in the distance.
Photographs by Edward Wigglesworth.



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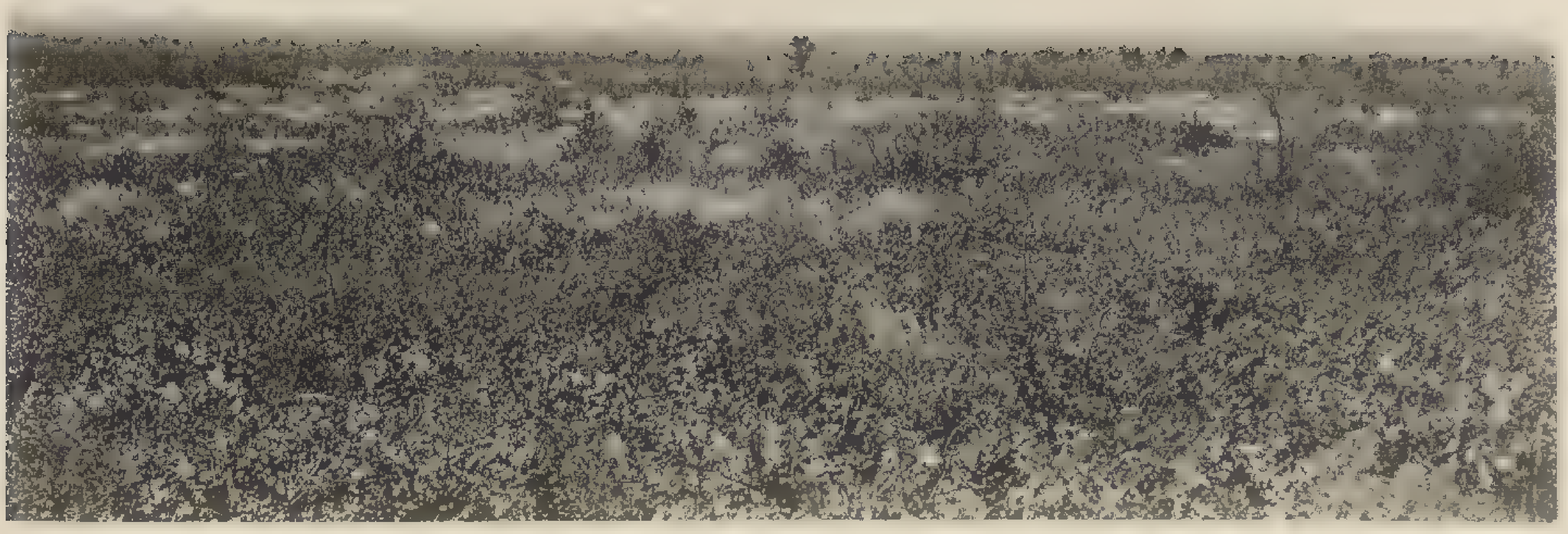

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HELIOTYPE CO. BOSTON

PLATE 16

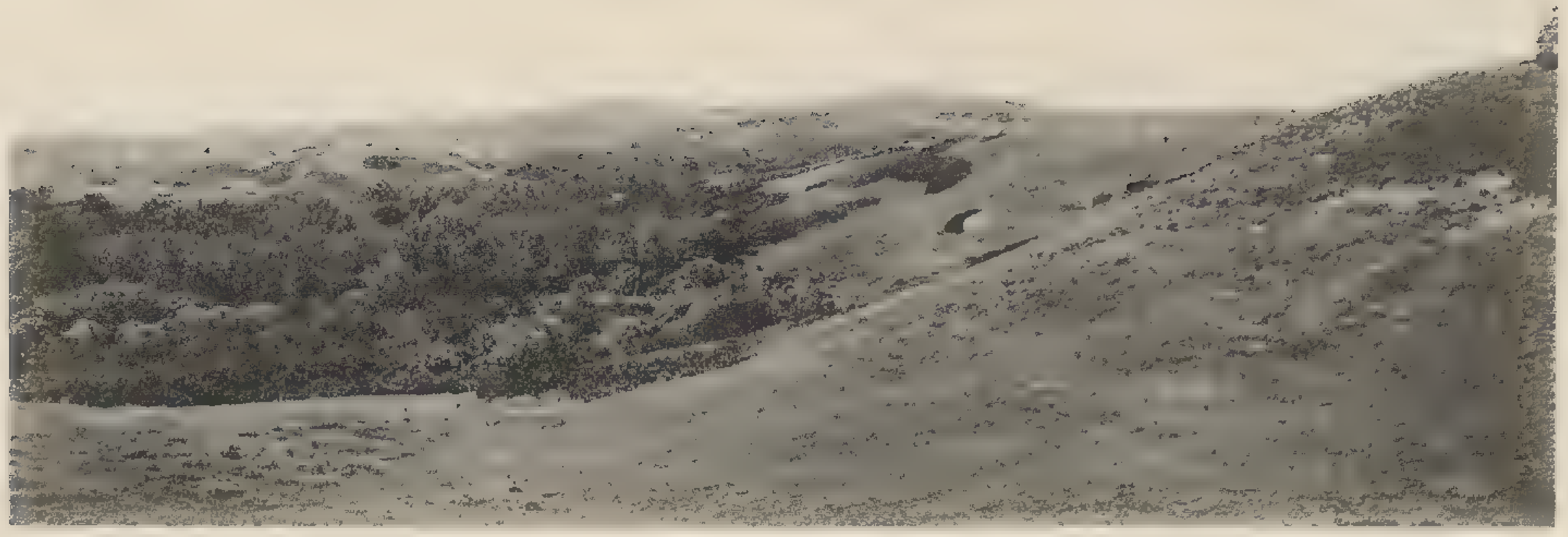
PLATE 16

Views of Marthas Vineyard upland

Fig. 1. Morainal topography of the western uplands, with pre-Wisconsin valley in foreground, slightly changed by ice action.

Fig. 2. Exposure of Cretaceous beds in morainal topography, showing almost no Wisconsin drift covering. In Peaked Hill district of Chilmark.

Photographs by Edward Wigglesworth.



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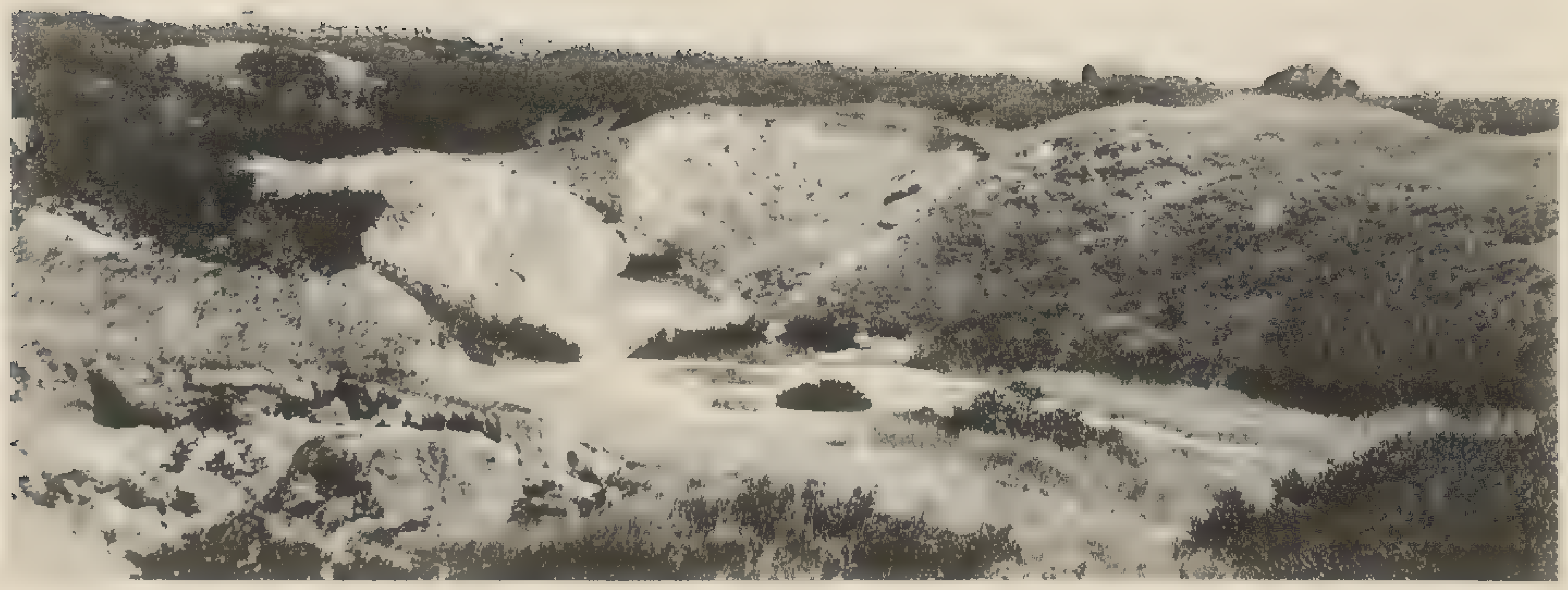

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HELIOTYPE CO. BOSTON

PLATE 17

PLATE **17**

Views of glacial details on Marthas Vineyard

Fig. 1. Subdued morainal topography west of Sengekontacket Pond; Cape Cod Bay glacial lobe.
Fig. 2. Morainal knob and boulders, Chilmark; Buzzards Bay lobe of the Wisconsin glacier.
Photographs by Edward Wigglesworth.

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HELIOTYPE CO. BOSTON

PLATE 18

PLATE 18

Views of glacial details on Marthas Vineyard

Fig. 1. Lower portion of Lagoon Pond, with Vineyard Haven in the distance. A submerged pre-Wisconsin valley.

Fig. 2. Ice contact slope and fosse north of West Tisbury.

Photographs by Edward Wigglesworth.

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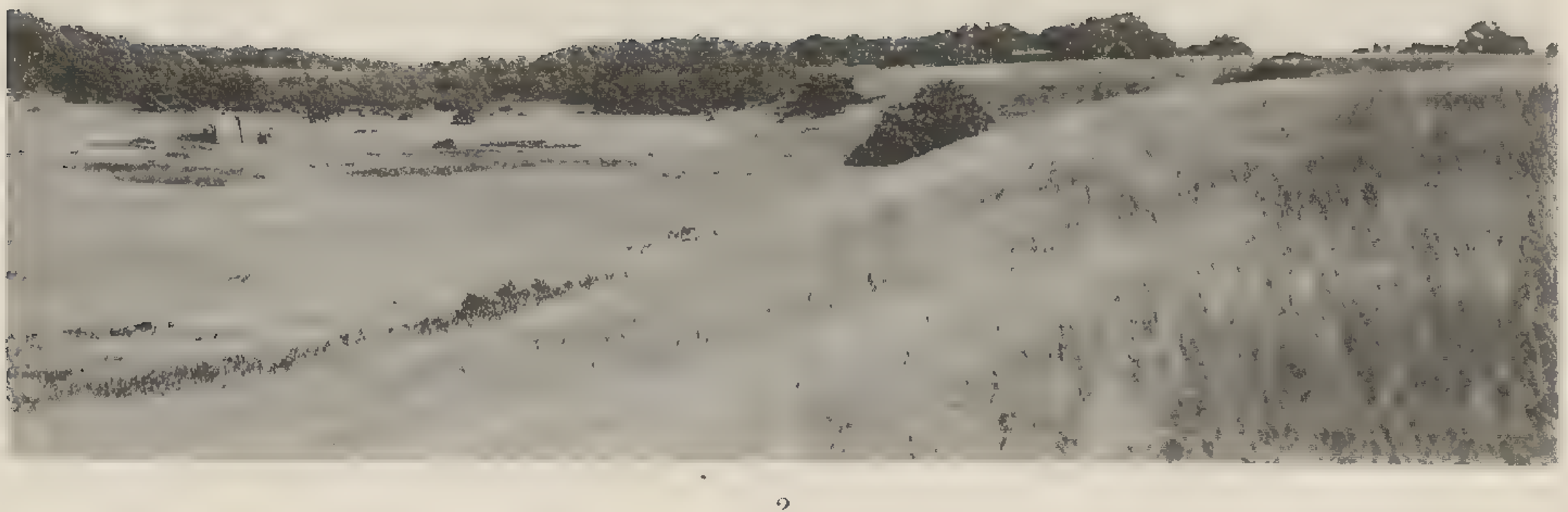

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HELIOTYPE CO., BOSTON

PLATE **19**

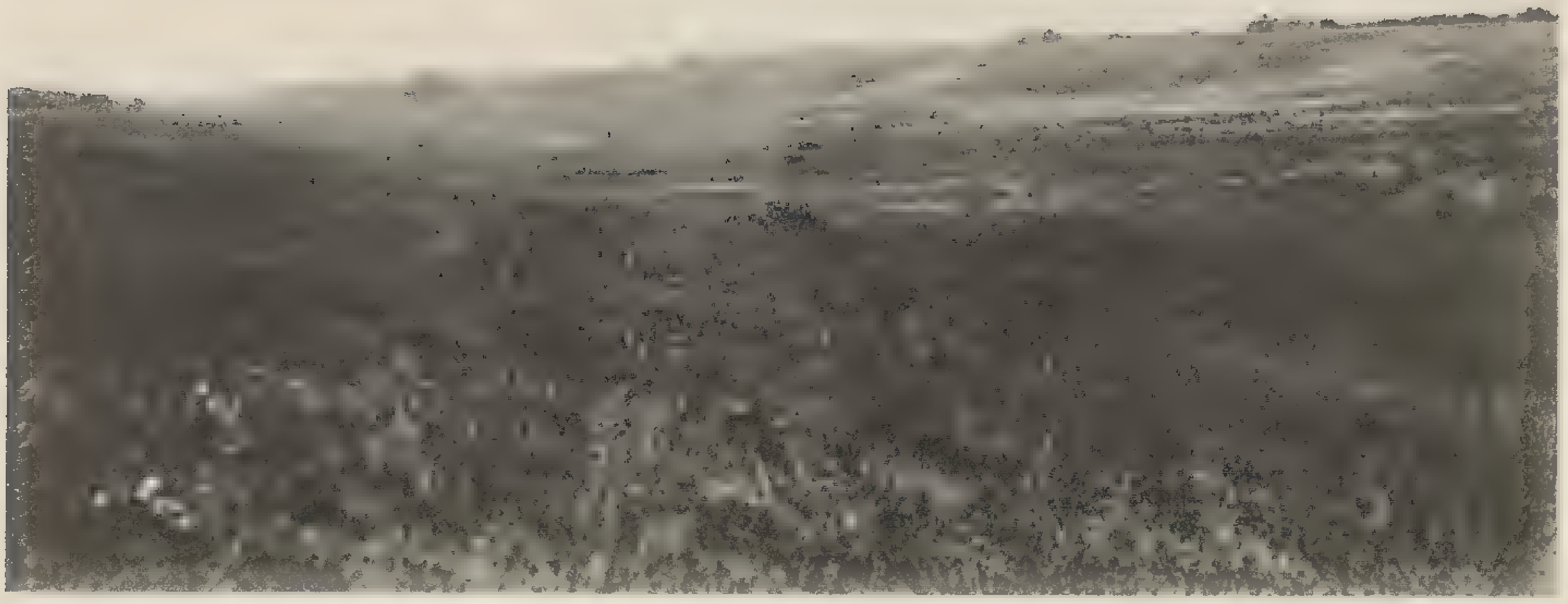
PLATE 19

Marthas Vineyard

Fig. 1. View of Oyster Pond channel, looking south. A typical drainage crease crossing the outwash plain.

Fig. 2. North end of Gay Head cliffs, the largest exposure of Cretaceous beds on the island.

Photographs by Edward Wigglesworth.



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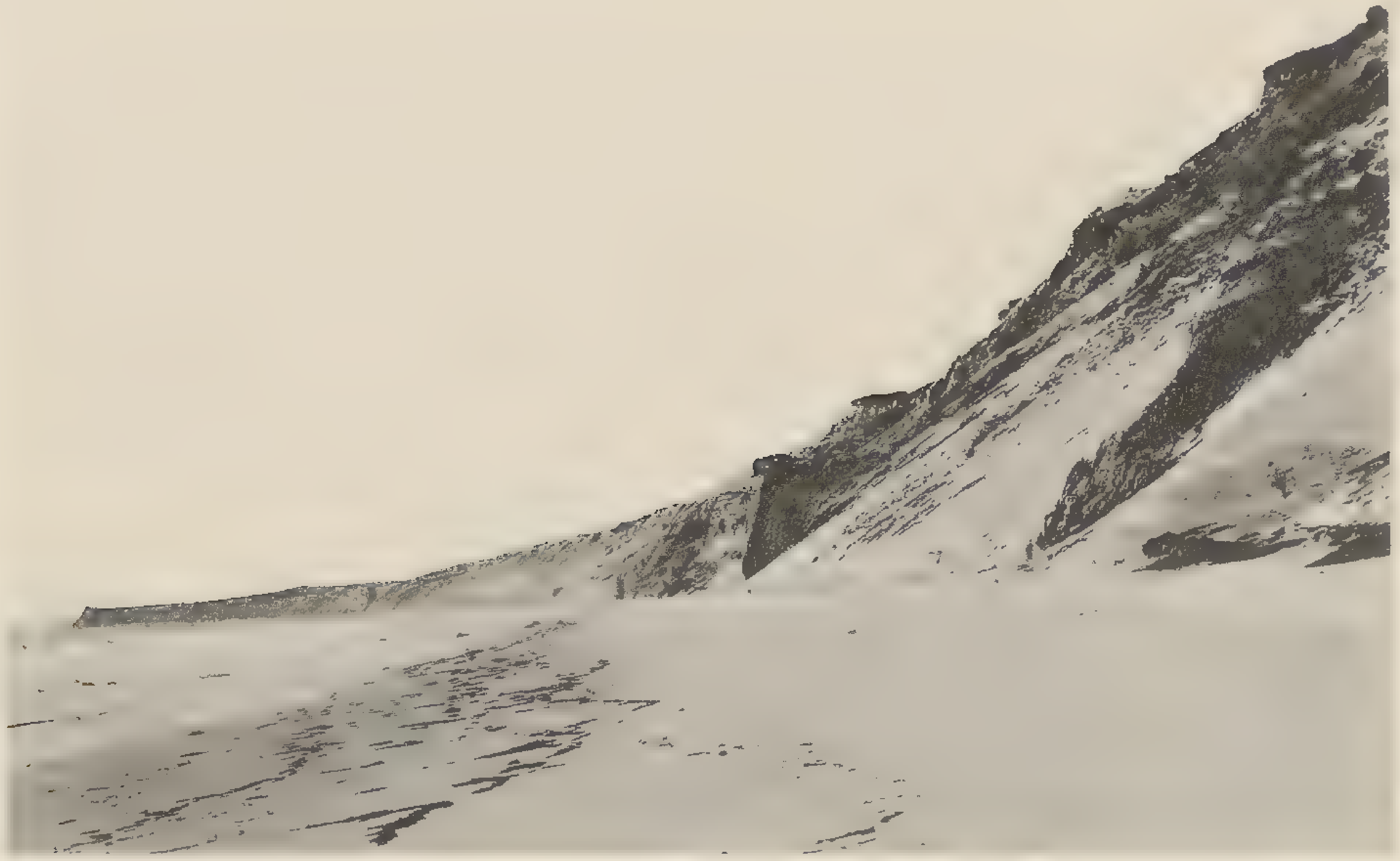
HELIOTYPE CO. BOSTON

PLATE 20

PLATE 20

Marthas Vineyard

Fig. 1. Nashaquitsa cliffs in 1915, looking west.
Fig. 2. The same cliffs, broken by landslips in the Gardiners clay.
Photographs by Edward Wigglesworth.



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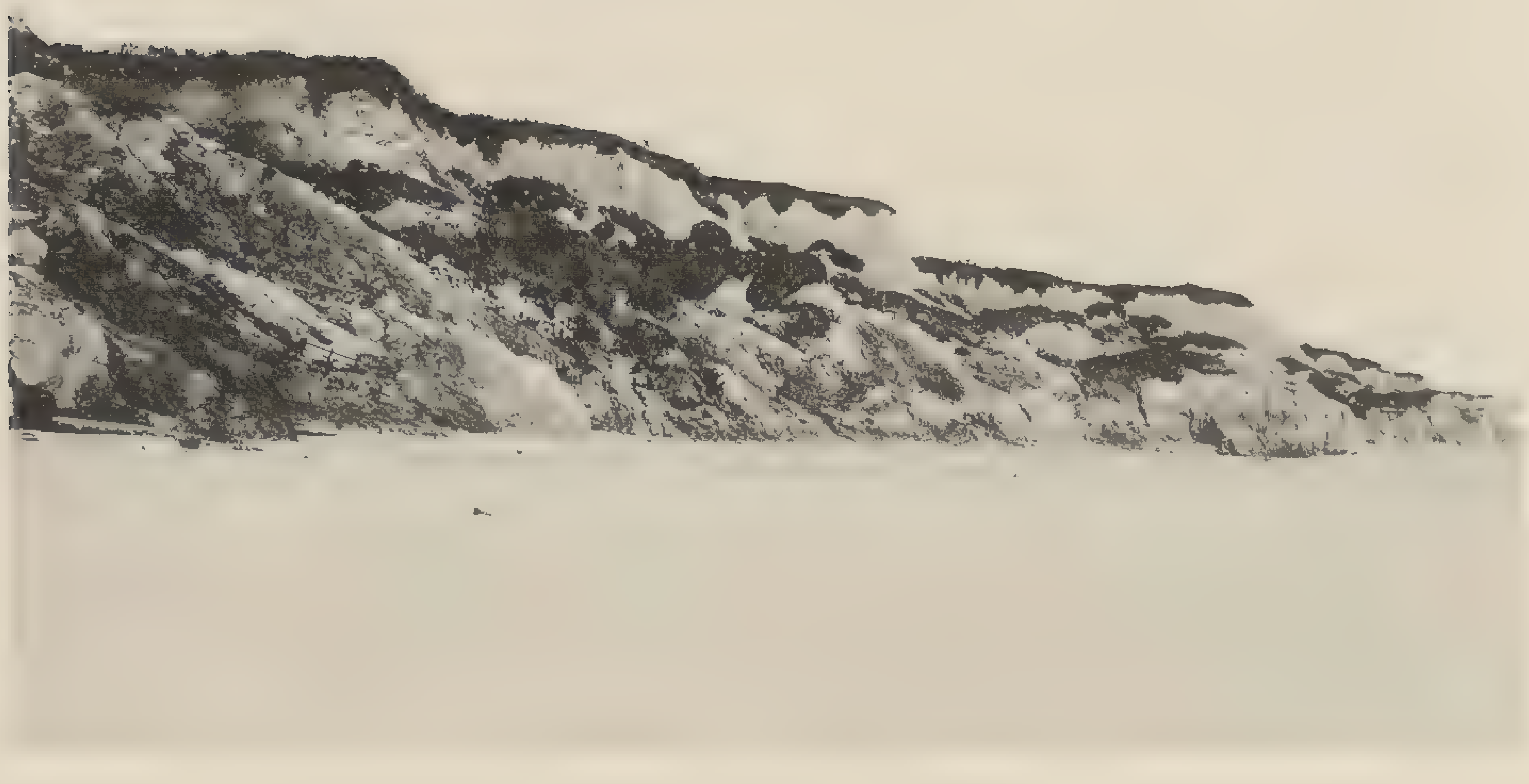

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HELIOTYPE CO. BOSTON

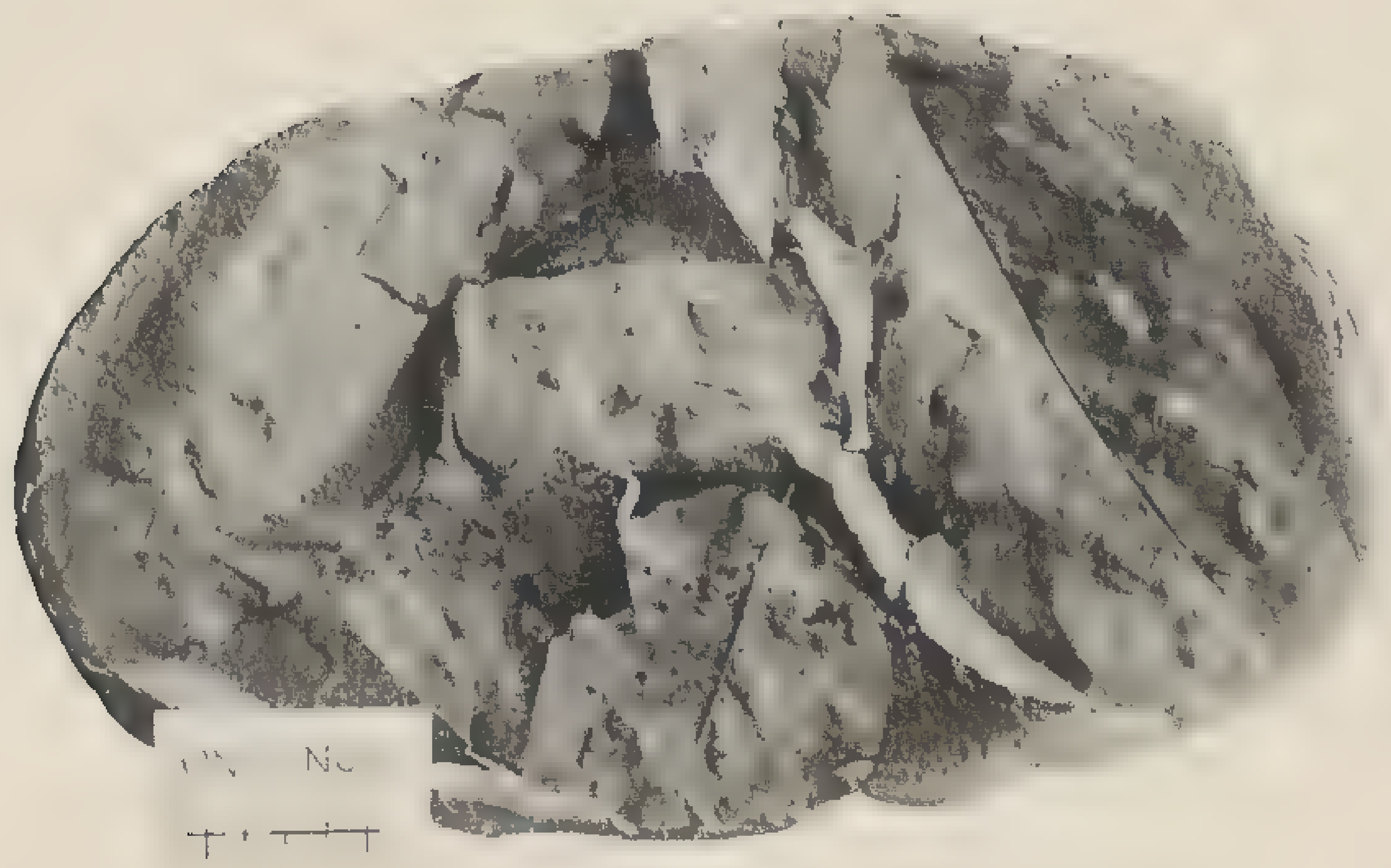
PLATE 21

PLATE **21**

Fossils from Upper Cretaceous beds in Gay Head Cliffs

Fig. 1. Leaf nodule from the plant-bearing beds. Original in the Harvard Geological Museum.

Fig. 2. Concretion from the clays folded under the lignite bed. Original in the Harvard Geological Museum.



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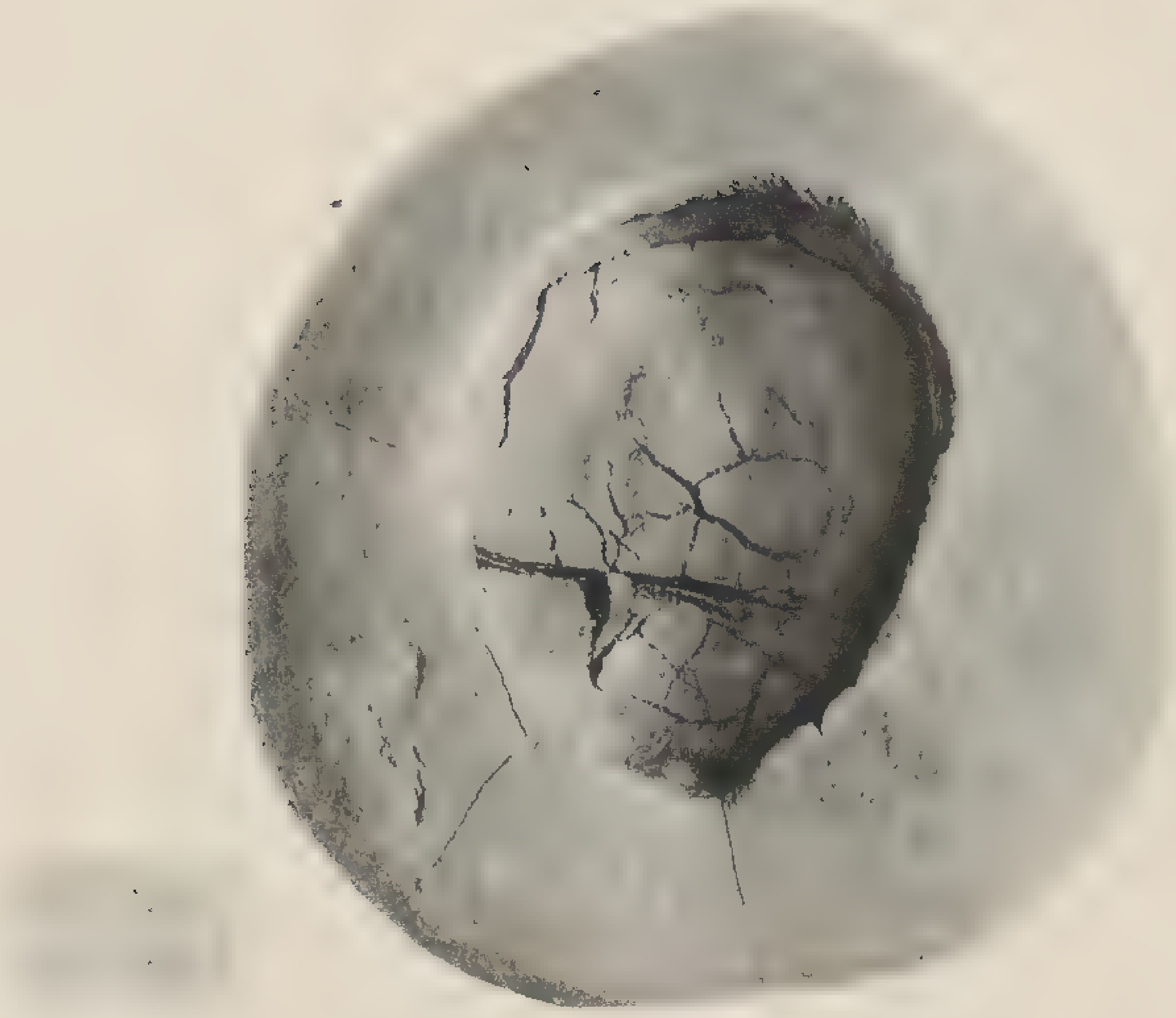

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HELIOTYPE CO. BOSTON

PLATE 22

PLATE **22**

Pleistocene fossils from the Aquinnah conglomerate at Gay Head.

Fig. 1. Astragalus of horse (*Equus? complicatus* Leidy).
Fig. 2. Metacarpal of camel (*Protocamelus?* sp.).
Fig. 3. a. Tooth of a whale (*Squalodon* sp.).
b. End view of the vertebra of a Dolphin.

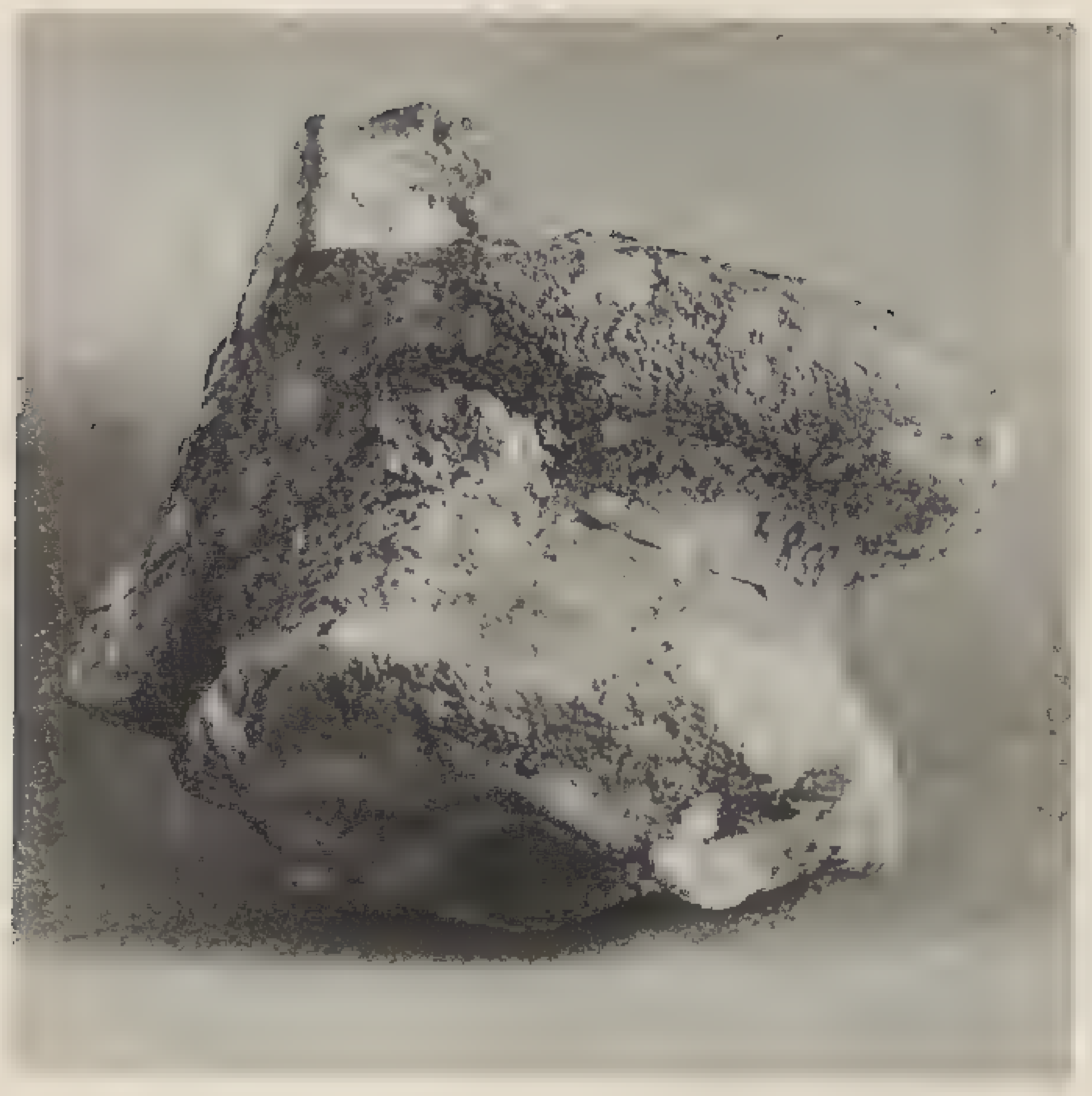

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PLATE 23

PLATE **23**

Marthas Vineyard

Fig. 1. Nashaquitsa cliffs. East end of section showing lowest Pleistocene gravels at right, Gardiners clay and sand at left, vertical boulder bed upturned (Moshup till) in center, as exposed on Sept. 4, 1916.

Fig. 2. Gardiners clay, underlying Manhasset formation southwest of Cape Higgon, on Vineyard Sound.

Photographs by Edward Wigglesworth.

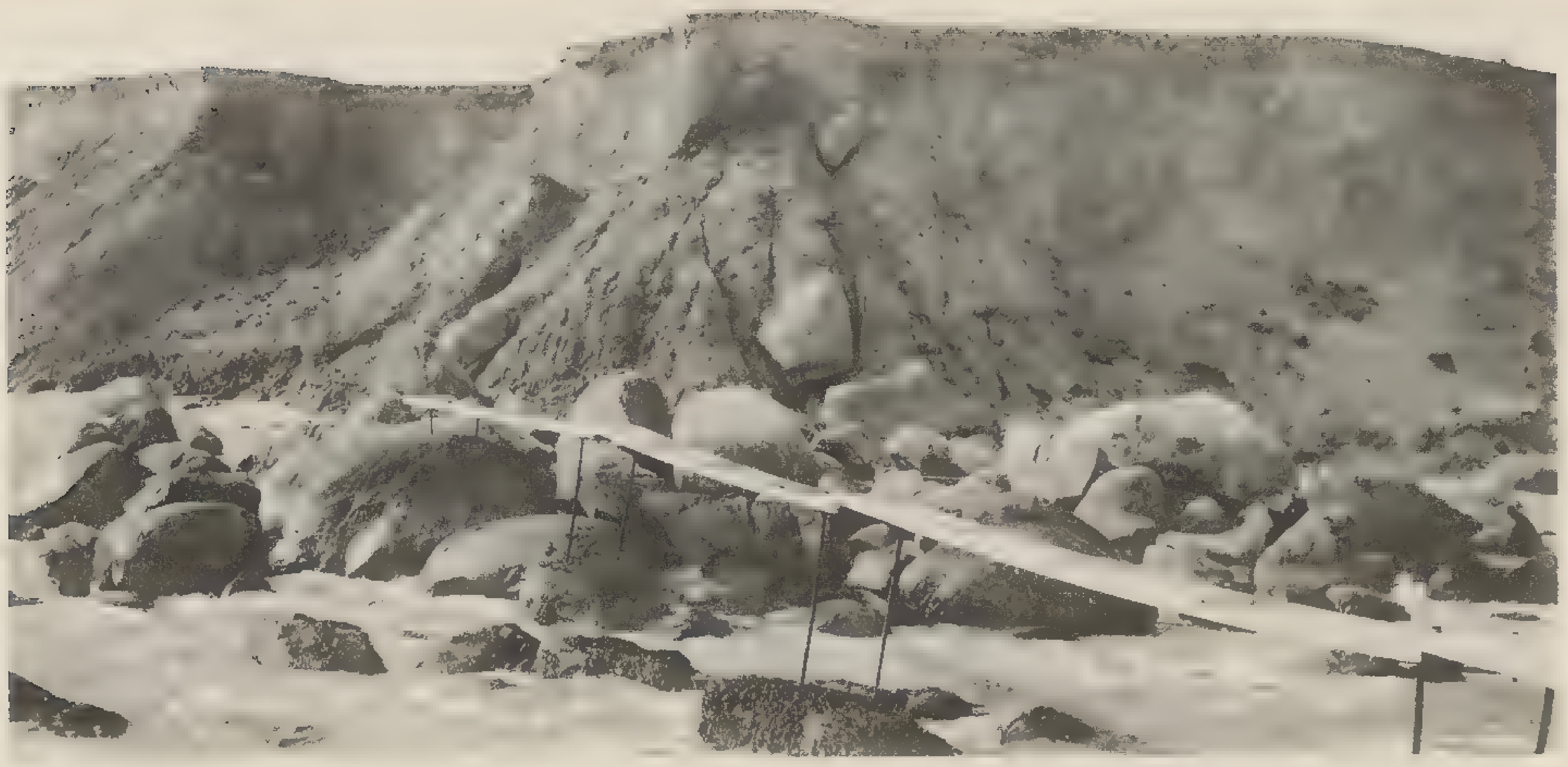

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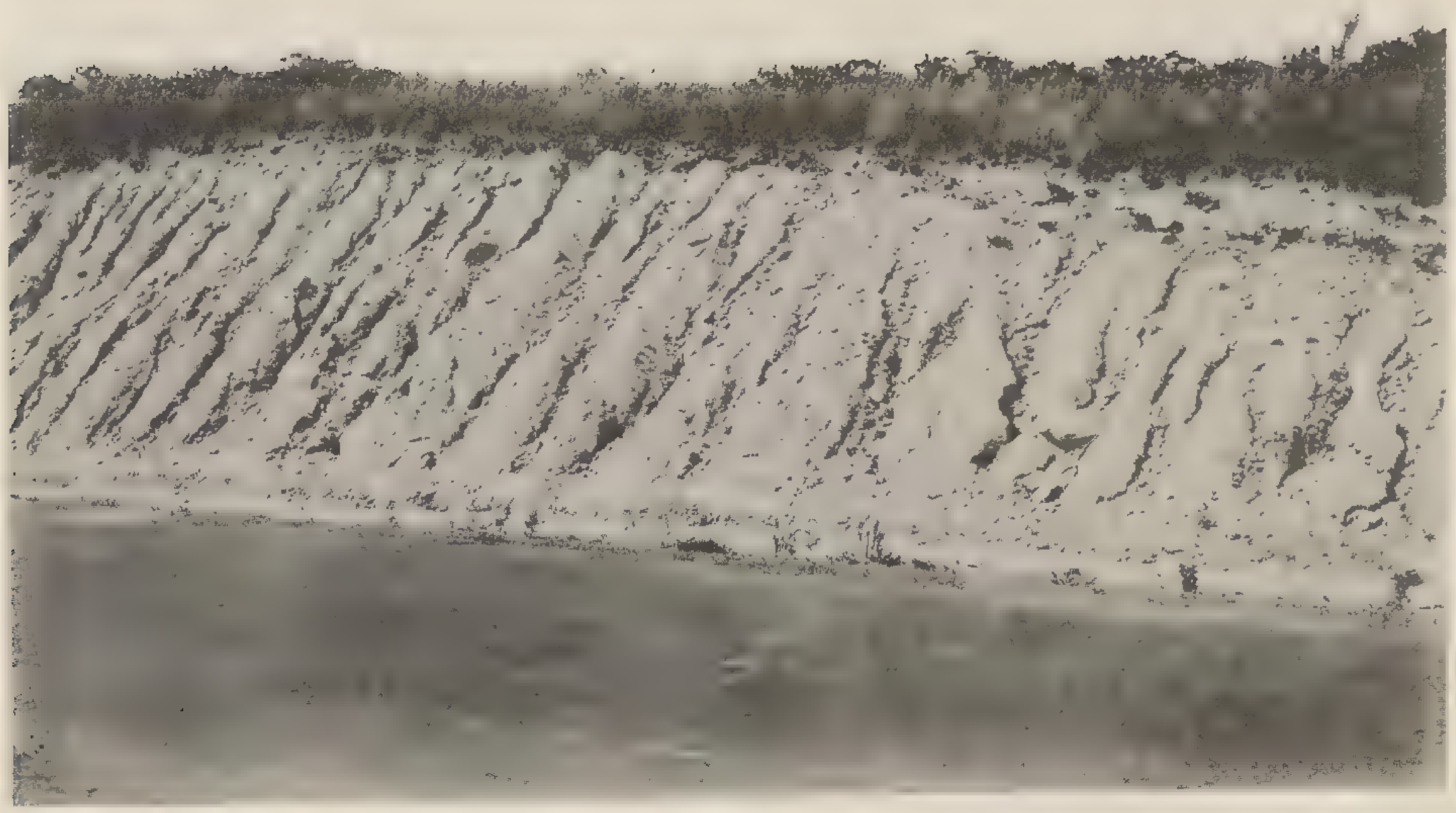
PLATE 24

PLATE 24

Marthas Vineyard

Fig. 1. Montauk till in road cut, town of Gay Head.
Fig. 2. Montauk till overlying Herod gravel. Stonewall Beach cliffs near west end.
Photographs by Edward Wigglesworth.



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HELIOTYPE CO. BOSTON

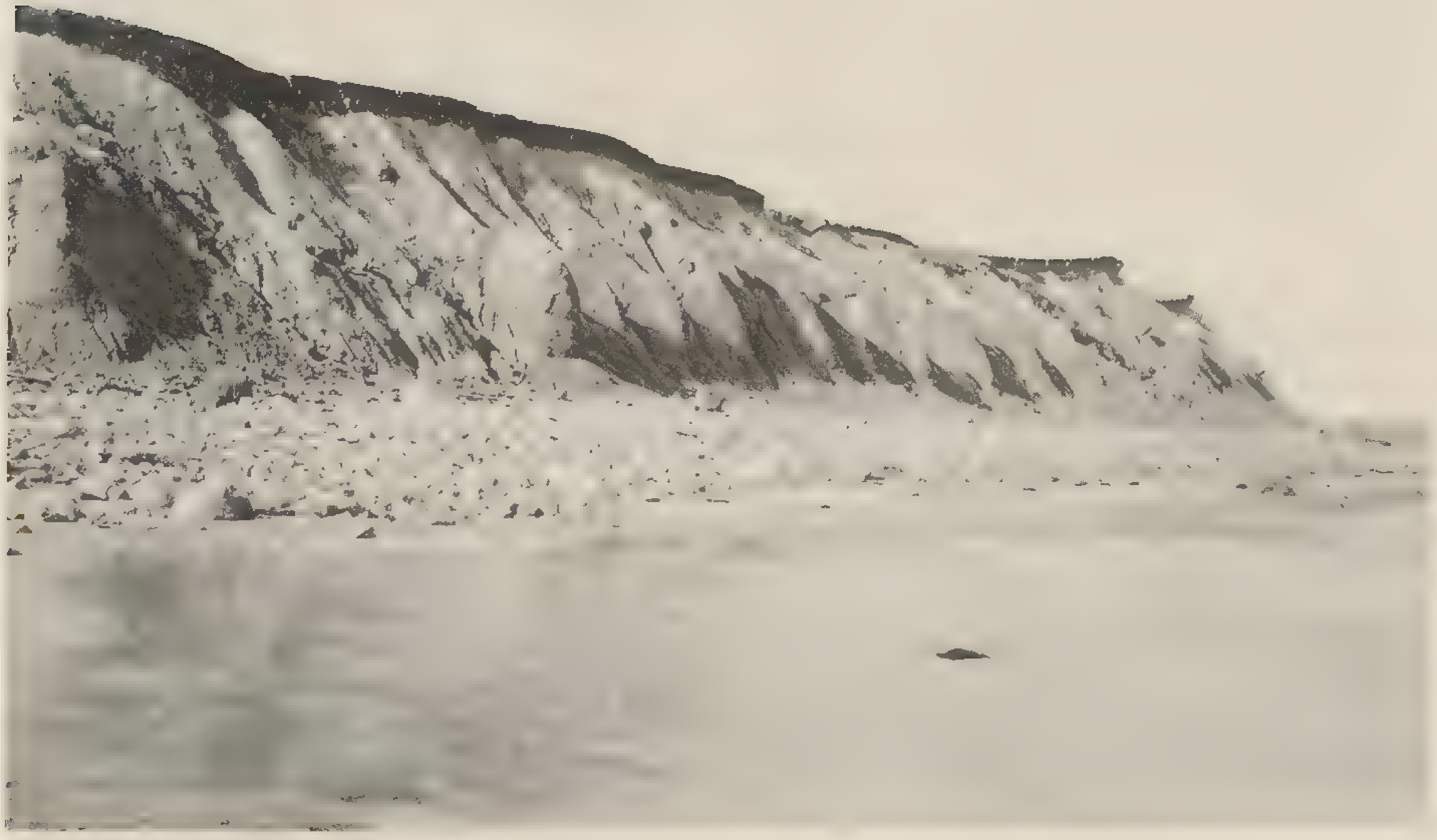
PLATE 25

PLATE 25

Views of Marthas Vineyard and Cape Cod

Fig. 1. Squibnocket cliffs, Marthas Vineyard. Montauk till showing characteristic erosion forms.

Fig. 2. Cape Cod. Old sea cliff on west side of Pilgrim Heights, as seen from railroad track in the marshes. The North Truro plain is above this cliff.



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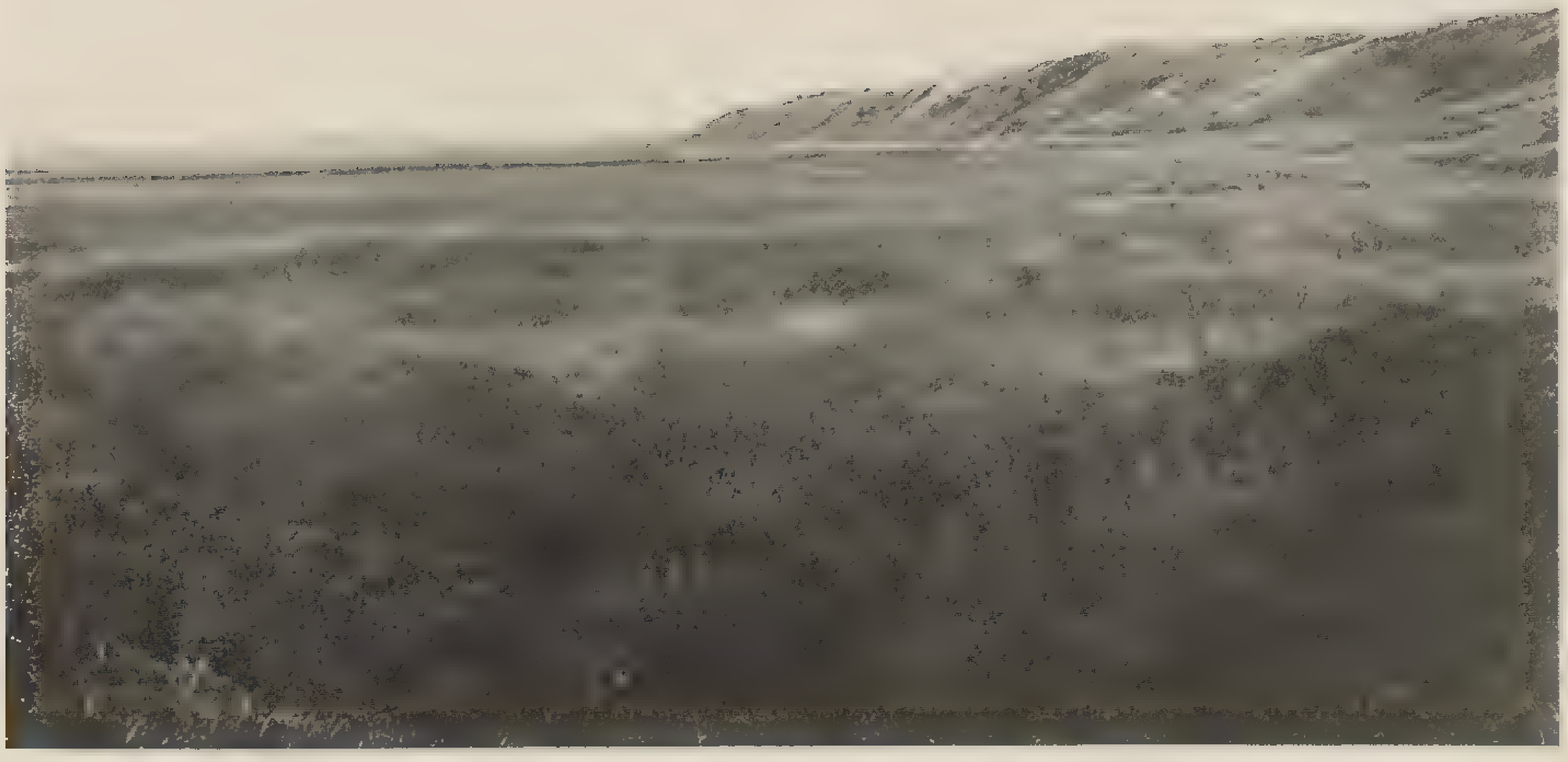

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HELIOTYPE CO. BOSTON

PLATE 26

PLATE 26

Topographic map of No Mans Land, part of Marthas Vineyard, Mass., and adjacent shoals.

(Contour interval 20 feet. Shore lines and topography on land from United States Geological Survey topographic map of Gay Head quadrangle. Soundings in feet at mean low water from United States Coast and Geodetic Survey Sheet No. 1210.) Drafting and editing supervised by the United States Geological Survey.

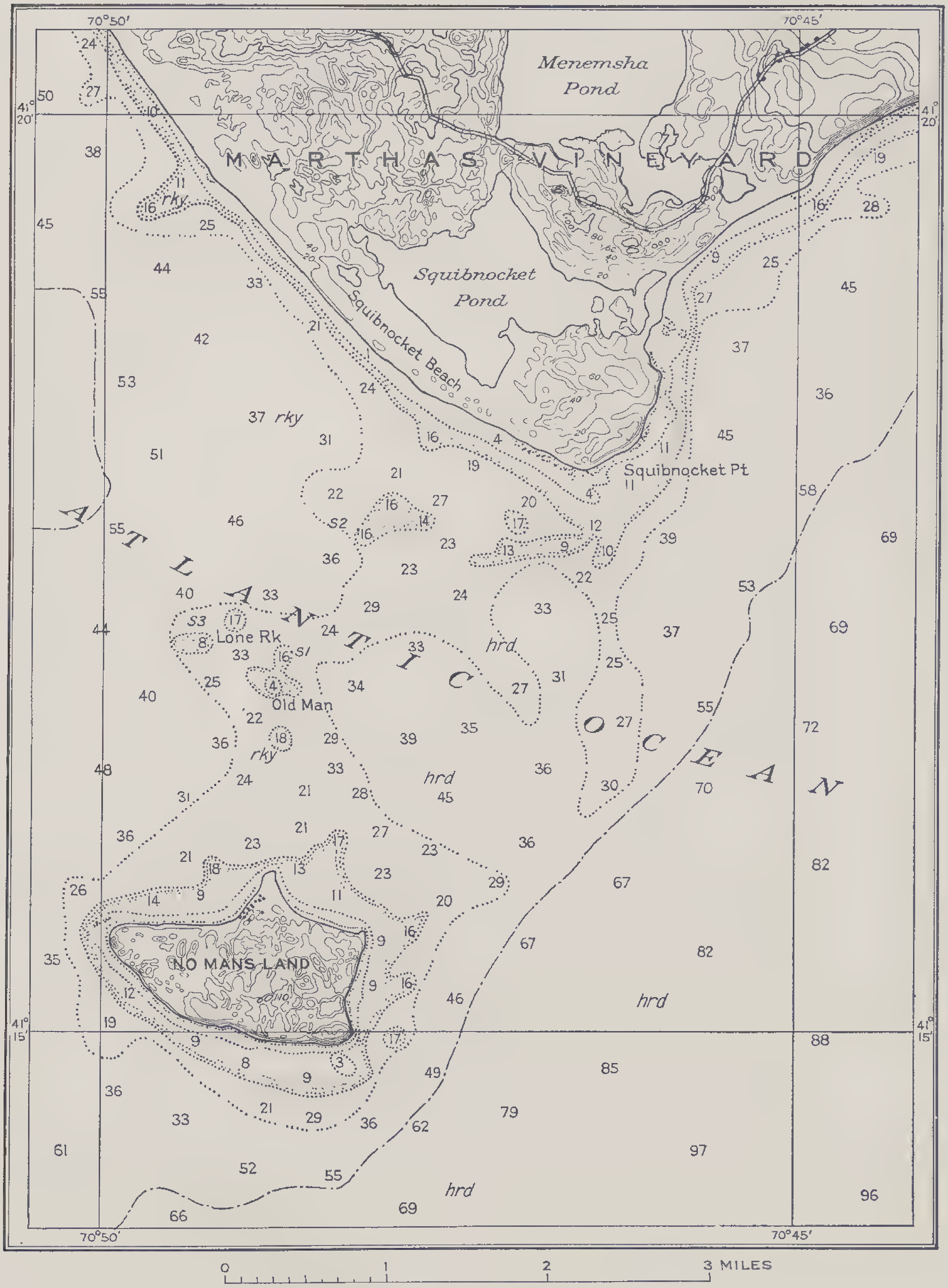

70°50′
70°45′
41° 20′
41° 15′
Menemsha Pond
MARTHAS VINEYARD
Squibnocket Pond
Squibnocket Beach
Squibnocket Pt
ATLANTIC OCEAN
Lone Rk
Old Man
NO MANS LAND
rky
hrd
0
1
2
3 MILES

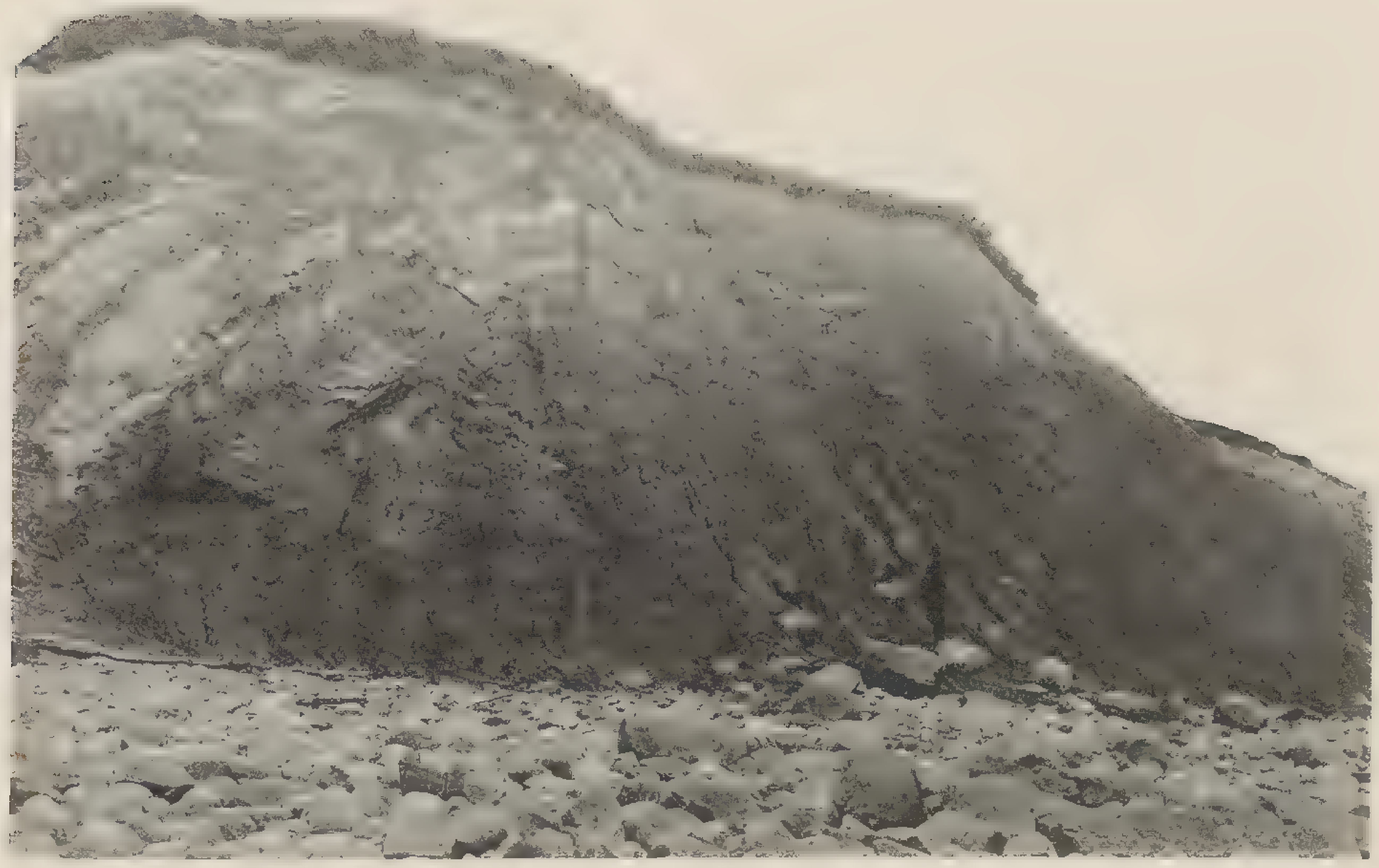
PLATE **27**

PLATE **27**

Glacial beds in the cliffs of No Mans Land

Fig. 1. Folded sand and Gardiners clay overlying Moshup till. One-half mile north of southeast point of the island, June 14, 1916.

Fig. 2. Boulder-bearing Montauk till in small bay near middle of the south side of the island; looking N. 24° W., June 14, 1916.



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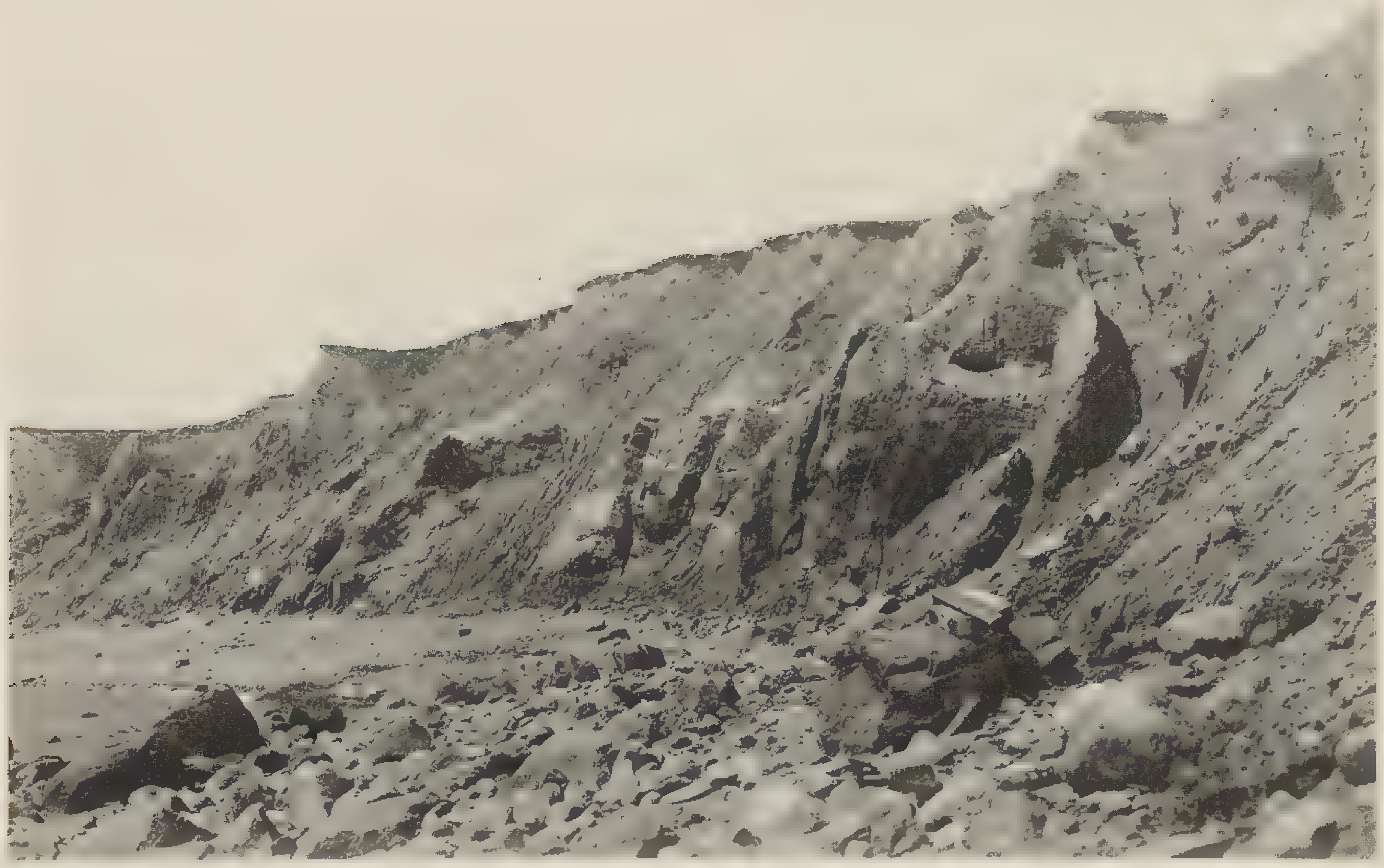

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HELIOTYPE CO. BOSTON

PLATE 28

PLATE 28

Views of No Mans Land

Fig. 1. View of the cliffs one-third mile east of southwest point of No Mans Land, on south shore June 14, 1916.

Fig. 2. Surface of No Mans Land at cliff edge, about half a mile east of the southwest point on south shore, June 14, 1916.

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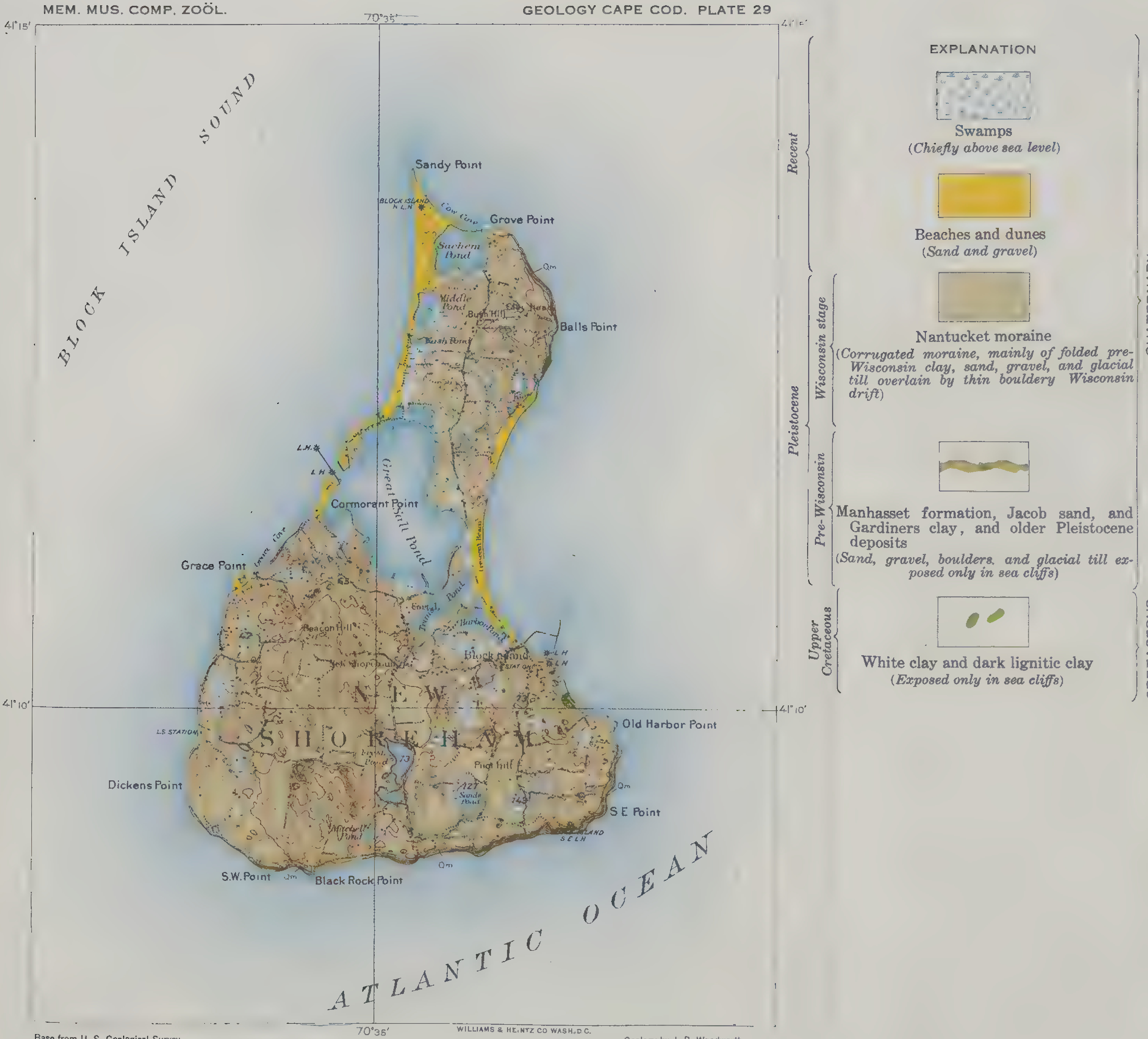
HELIOTYPE CO. BOSTON

PLATE 29

PLATE 29

Geologic Map of Block Island

Base from United States Geological Survey topographic map of Block Island quadrangle. Geology by J. B. Woodworth, United States Geological Survey, 1915–1916. Drafting and editing under the supervision of the United States Geological Survey.



Base from U. S. Geological Survey topographic map of Block Island quadrangle, reprinted from earlier editions without revision

GEOLOGIC MAP OF BLOCK ISLAND, R.I.

Scale $\frac{1}{62,500}$

1 ½ 0 1 2 Miles

1 ½ 0 1 2 Kilometers

Contour interval 20 feet

Datum is mean sea level

Geology by J. B. Woodworth, U. S. Geological Survey, 1915–16

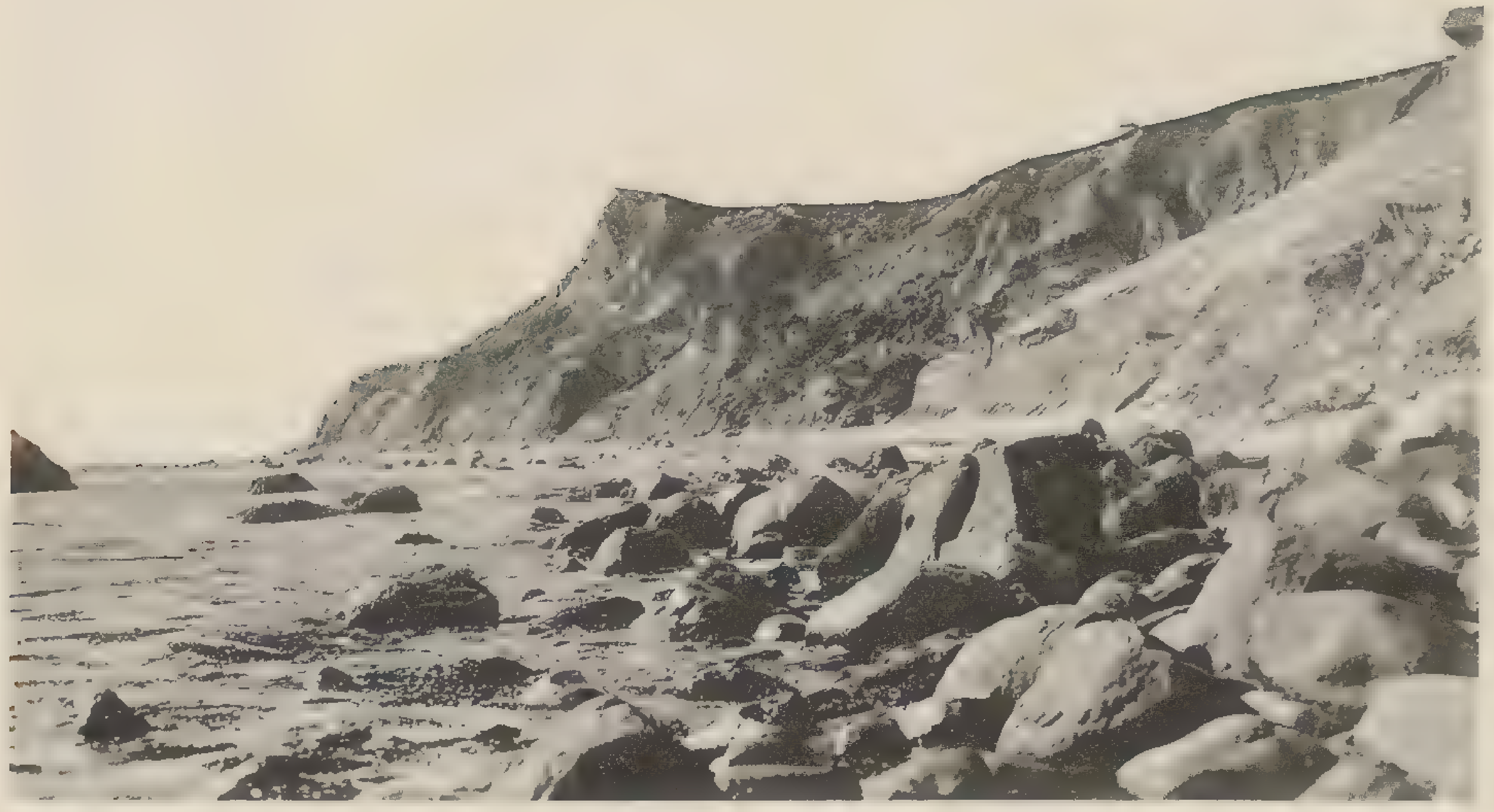
PLATE 30

PLATE **30**

Glacial deposits, Mohegan Bluffs, Block Island

Fig. 1. Southeast point, looking southwest. Gardiners clay on beach in foreground under Jacob sand. Manhasset formation with Montauk till member in background of cliff.

Fig. 2. View west of Southeast Point, Block Island, looking eastward at pinnacles of Montauk boulder clay. October 31, 1915.



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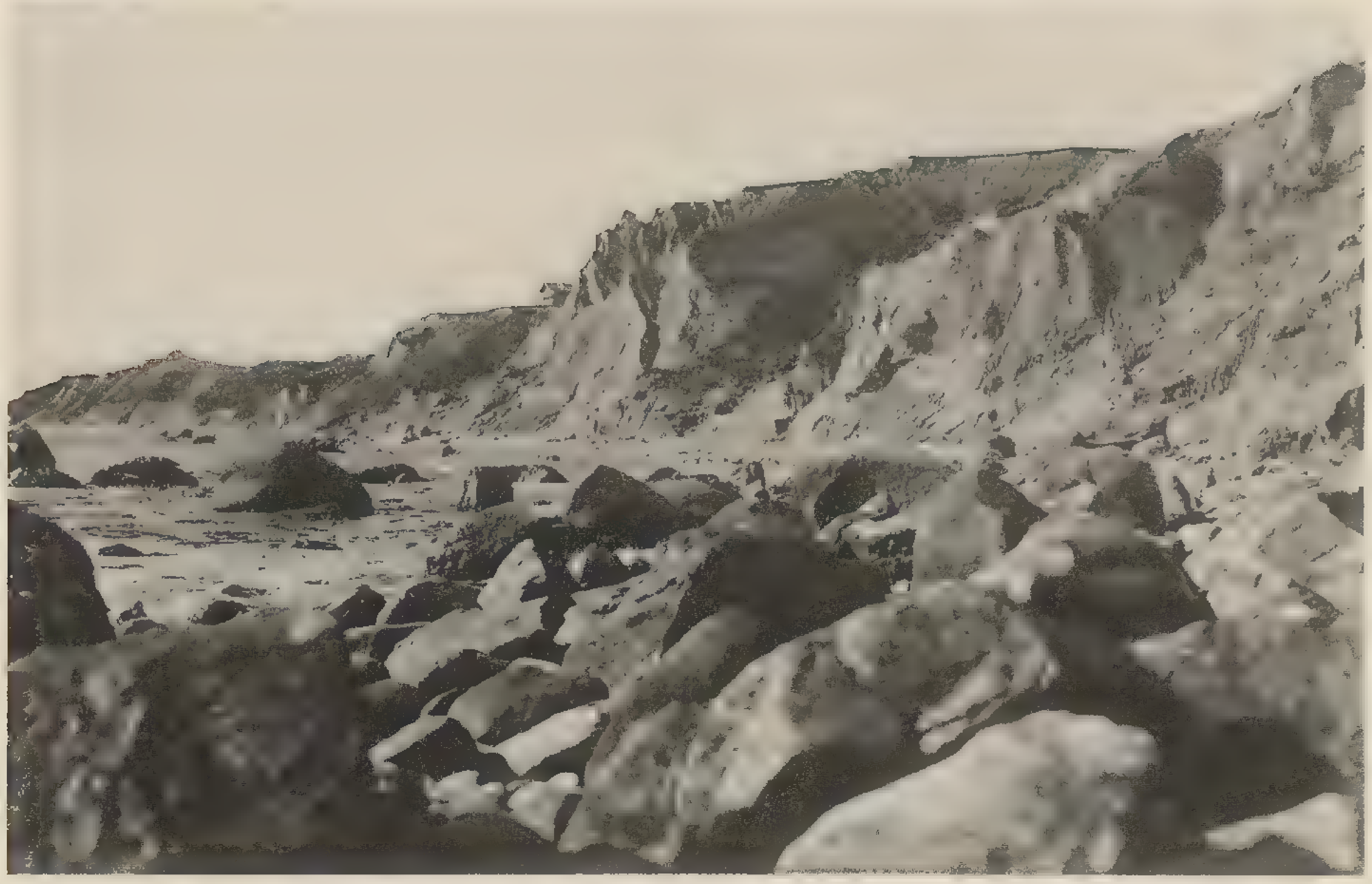

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HELIOTYPE CO. BOSTON

PLATE **31**

PLATE **31**

Surface features of Block Island

Fig. 1. View showing configuration of the surface of Block Island, south of Beacon Hill.
Fig. 2. Sand dune on Crescent Beach, east coast of Block Island.

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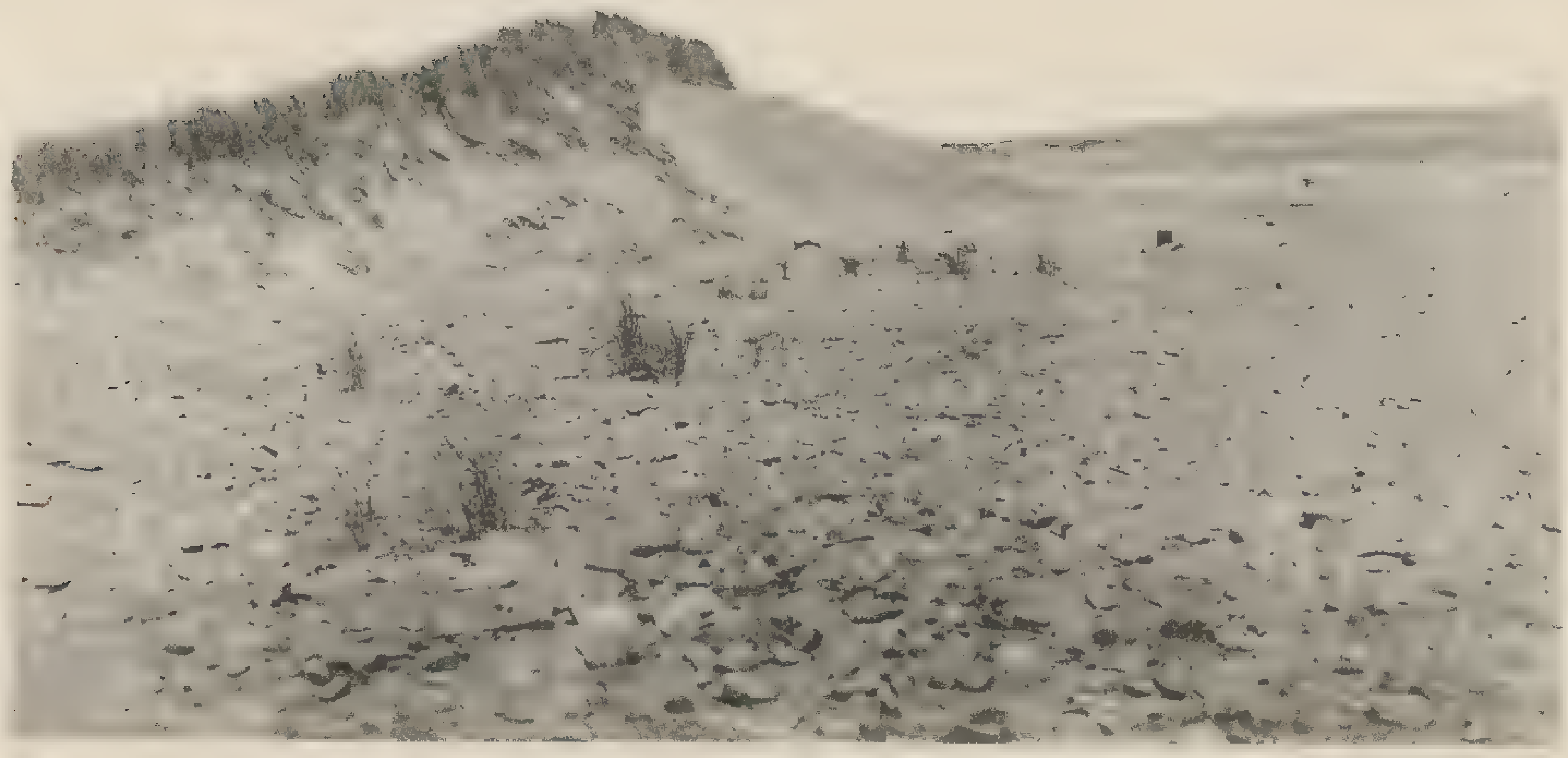

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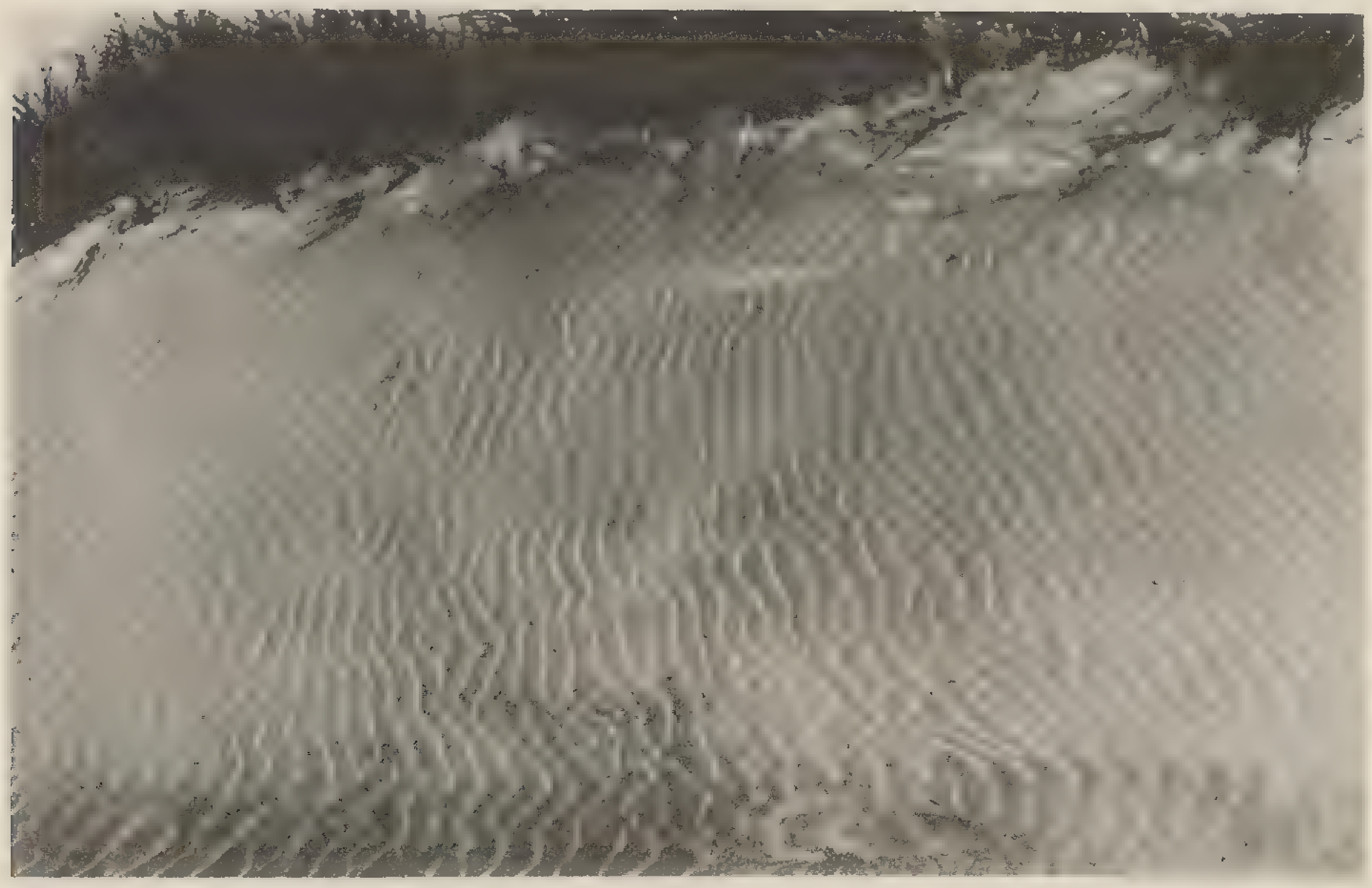
HELIOTYPE CO. BOSTON

PLATE 32

PLATE **32**

Block Island

Fig. 1. Wind ripples on black magnetic sand.
Fig. 2. Remains of device for magnetic separation of black iron sand of the Crescent Beach dunes.



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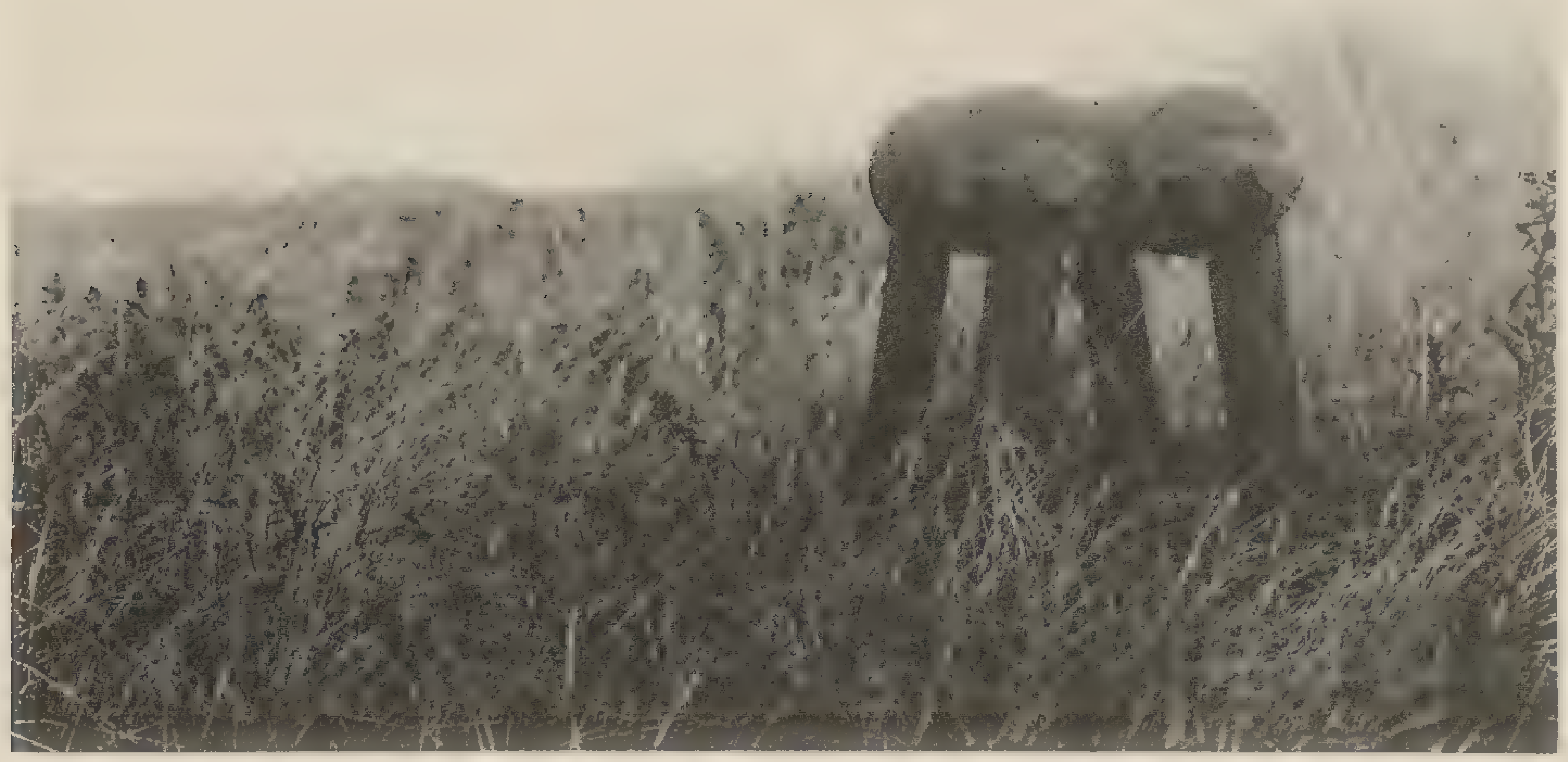

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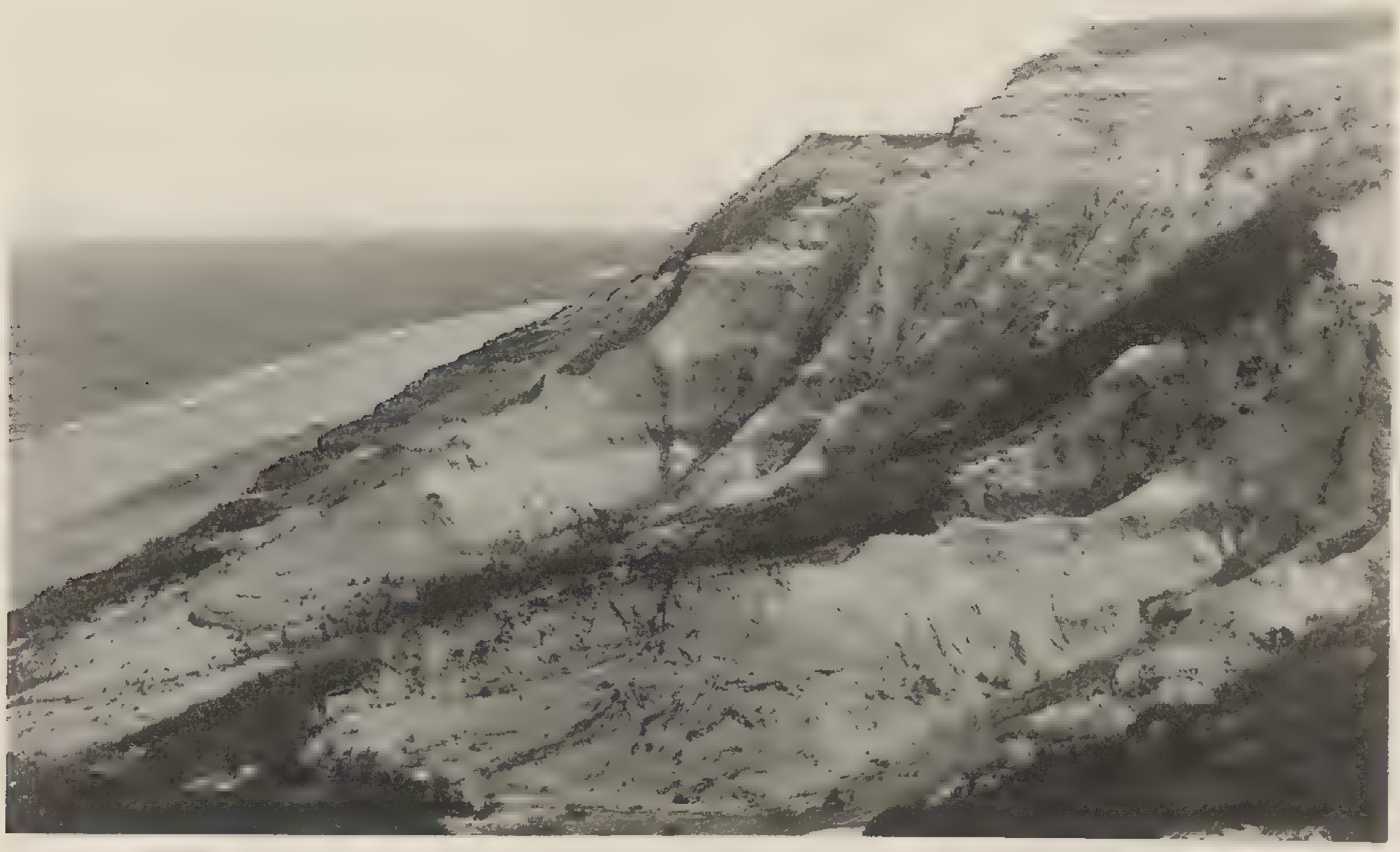
PLATE 33

PLATE **33**

Exposures of Gardiners (?) clay on Cape Cod.

Fig. 1. The "clay pounds" at Highland Light, near the wireless station. Jameco (?) gravel at base, Gardiners (?) clay in the middle, and Jacob (?) sand at the top of the section.

Fig. 2. Gardiners (?) clay exposed in anticlinal fold on Nickerson's Neck, south shore of Pleasant Bay near Chatham. Looking S. 70° W, July 28, 1916.



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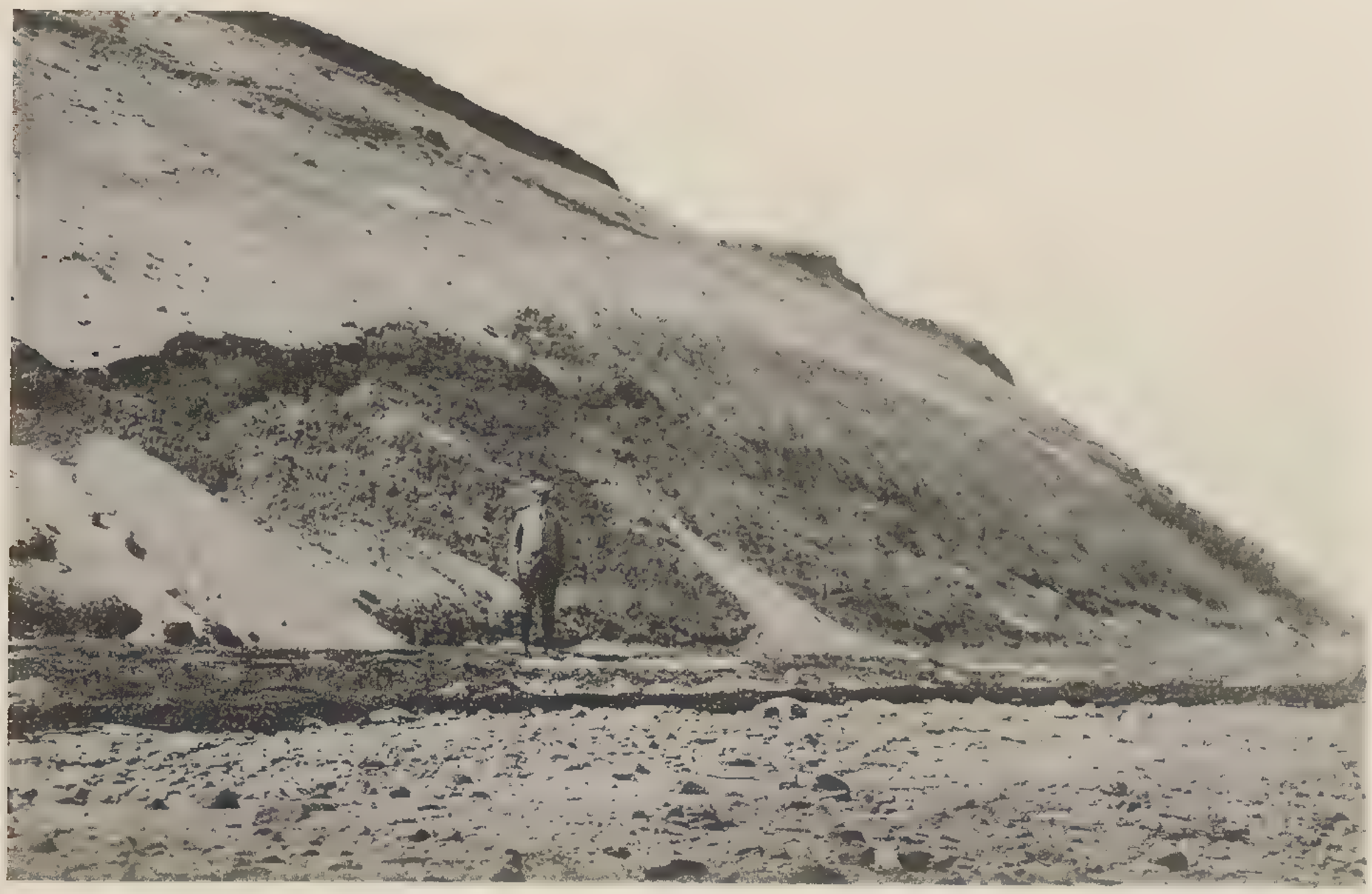

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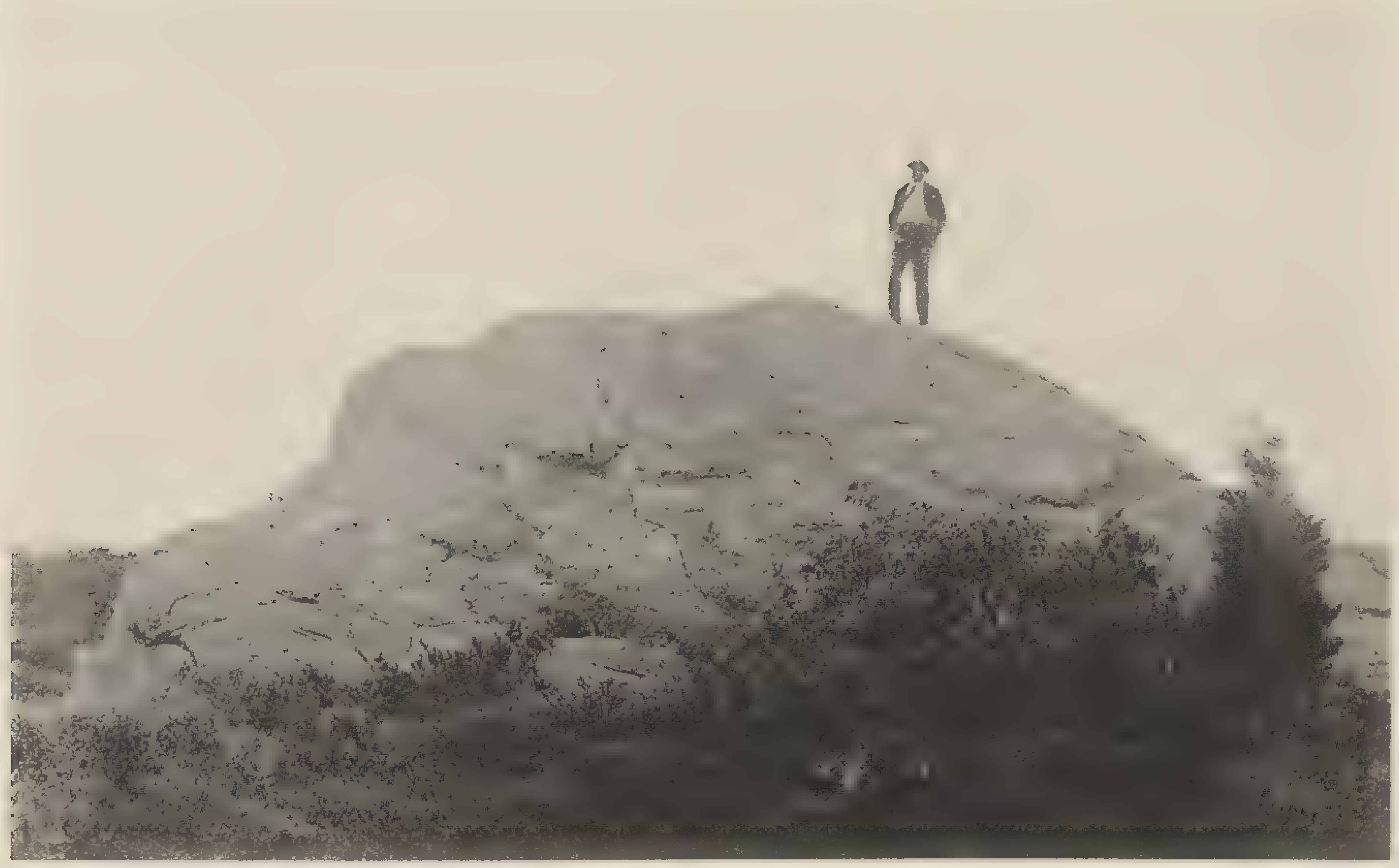
PLATE **34**

PLATE 34

Views of Cape Cod

Fig. 1. Enos Rock in Eastham. A granite boulder from the South Channel lobe of the Wisconsin ice sheet.

Fig. 2. The sea cliff at Chatham in front of the old lighthouse.



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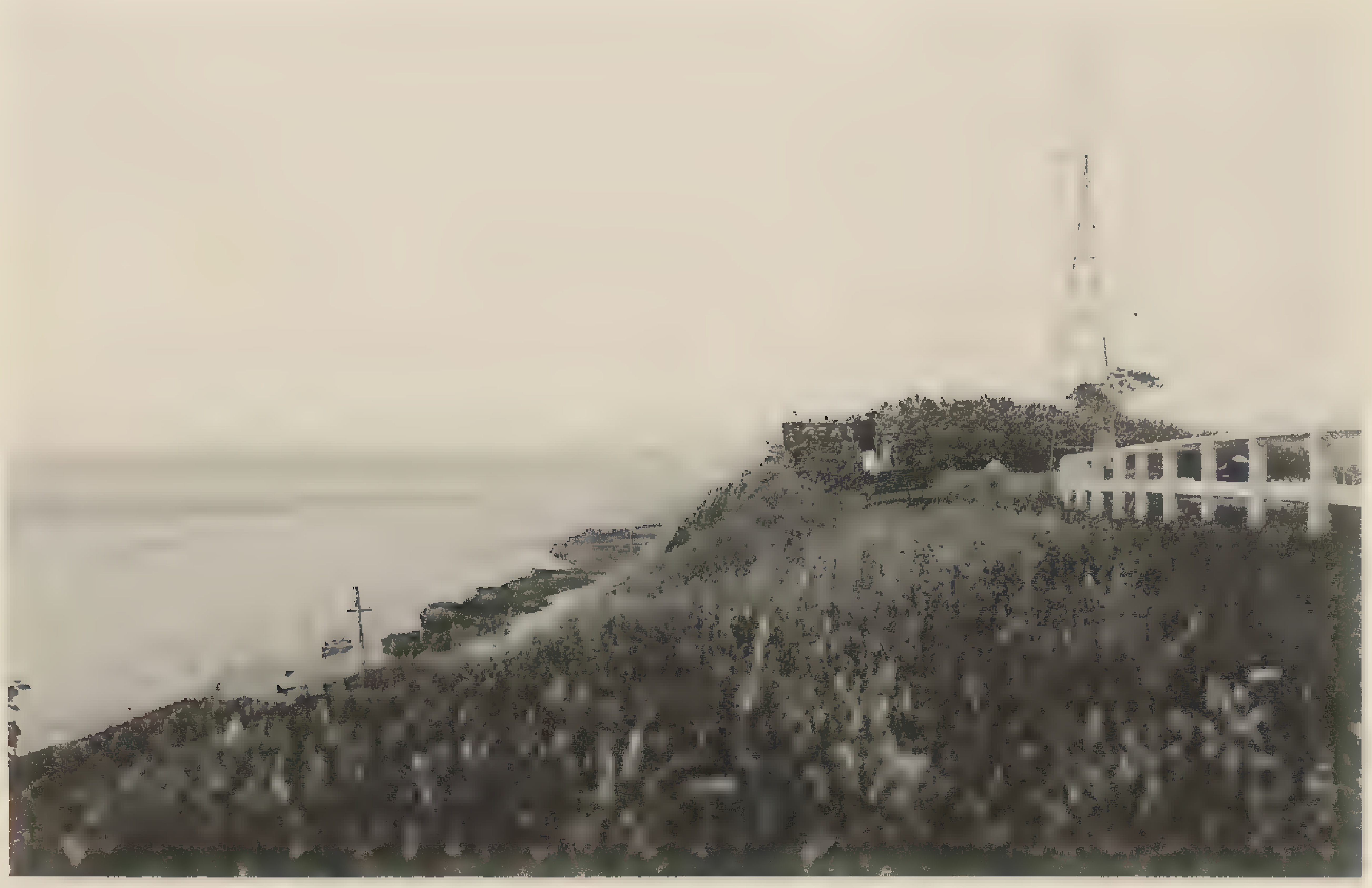

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HELIOTYPE CO. BOSTON

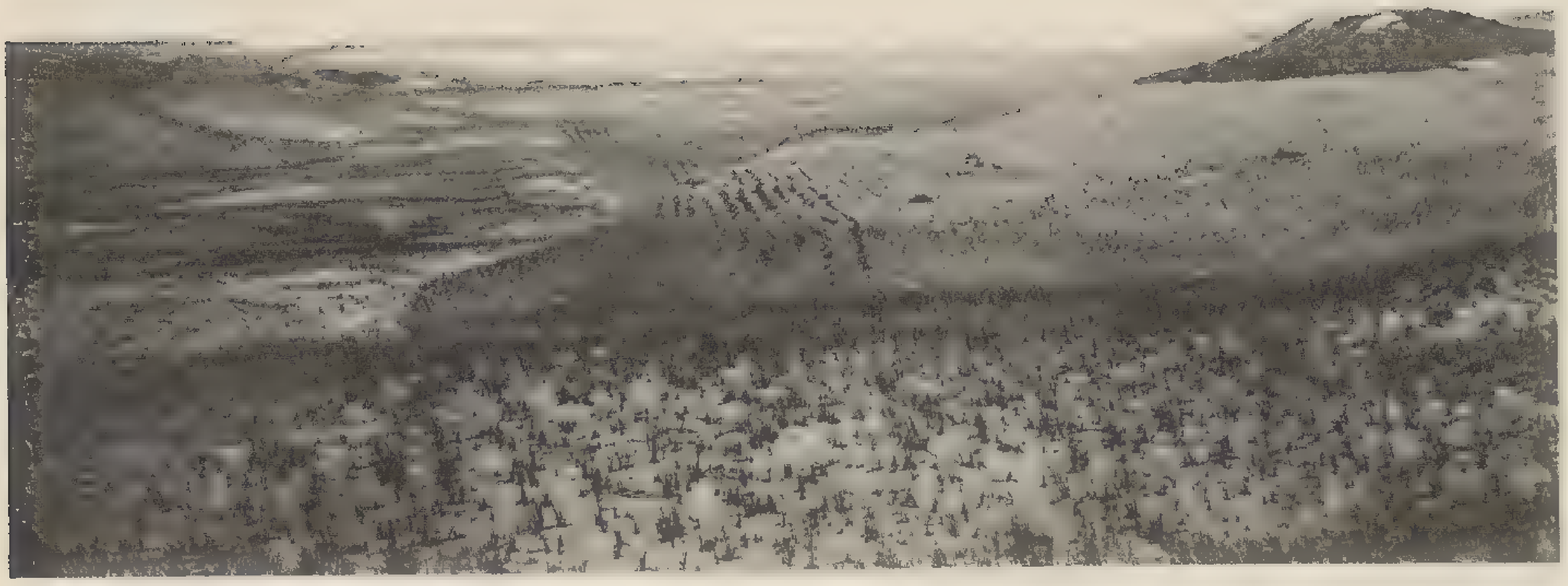
PLATE 35

PLATE 36

PLATE **36**

Views of Cape Cod

Fig. 1. Panorama of dune ridges about 1½ miles northeast of Pilgrim Monument.
Fig. 2. Lee side of old sand dune near Duck Pond north of Provincetown.
Photographs by T. Wayland Vaughan.



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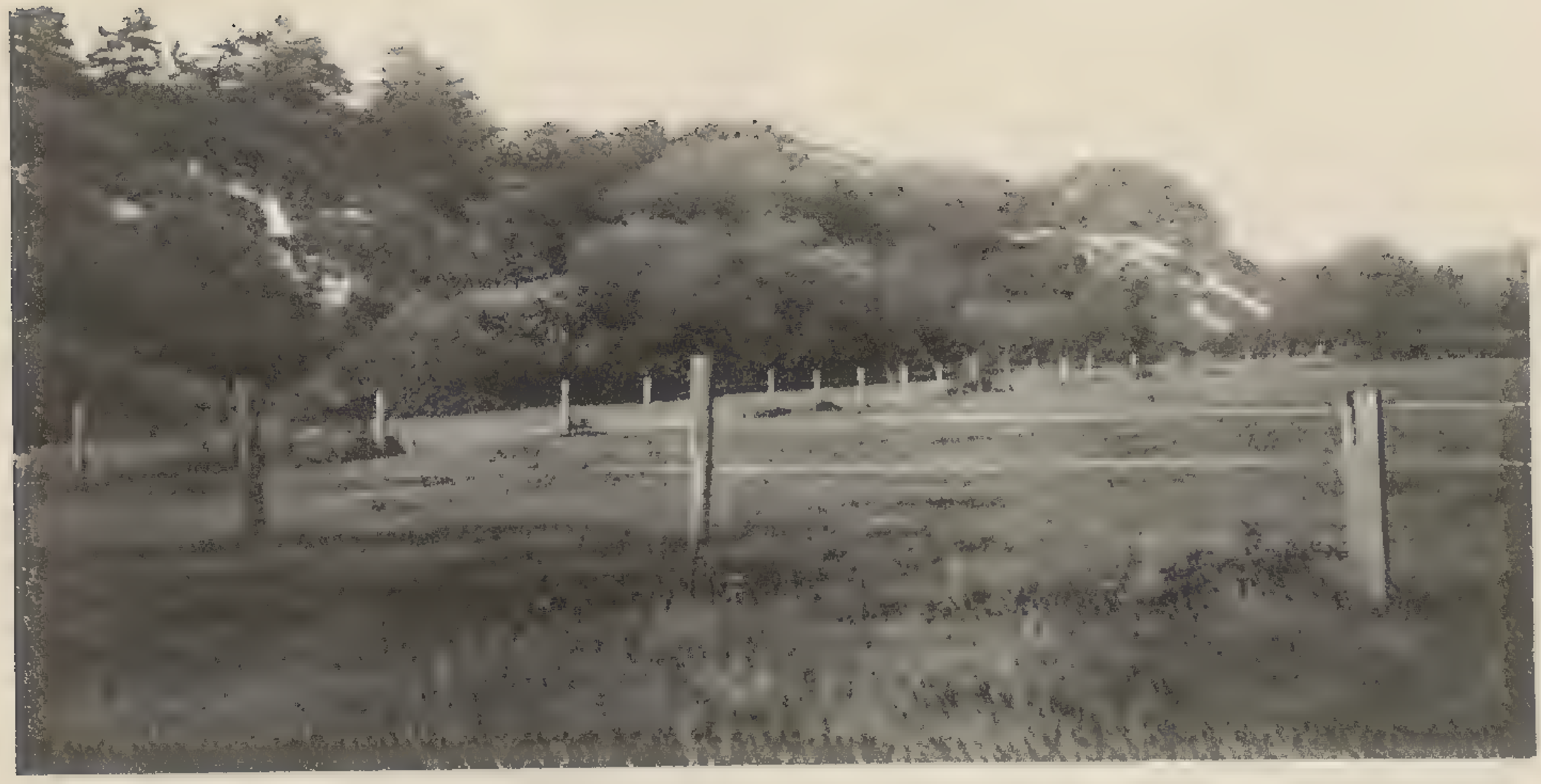

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PLATE **37**

PLATE **37**

Fig. 1. Marsh growth at head of old harbor, Wellfleet, Cape Cod.
Fig. 2. Edge of natural forest on south shore of Naushon Island.

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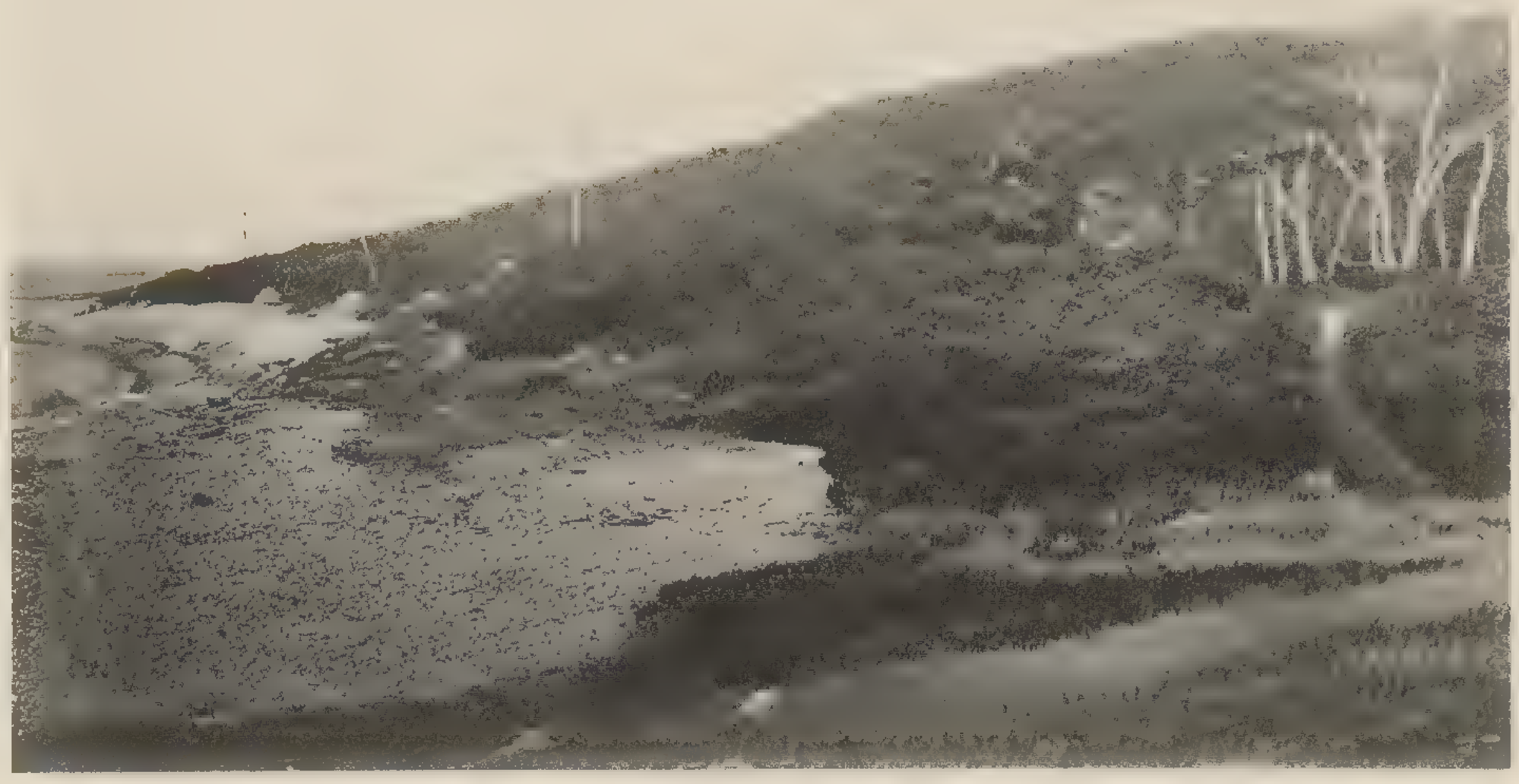

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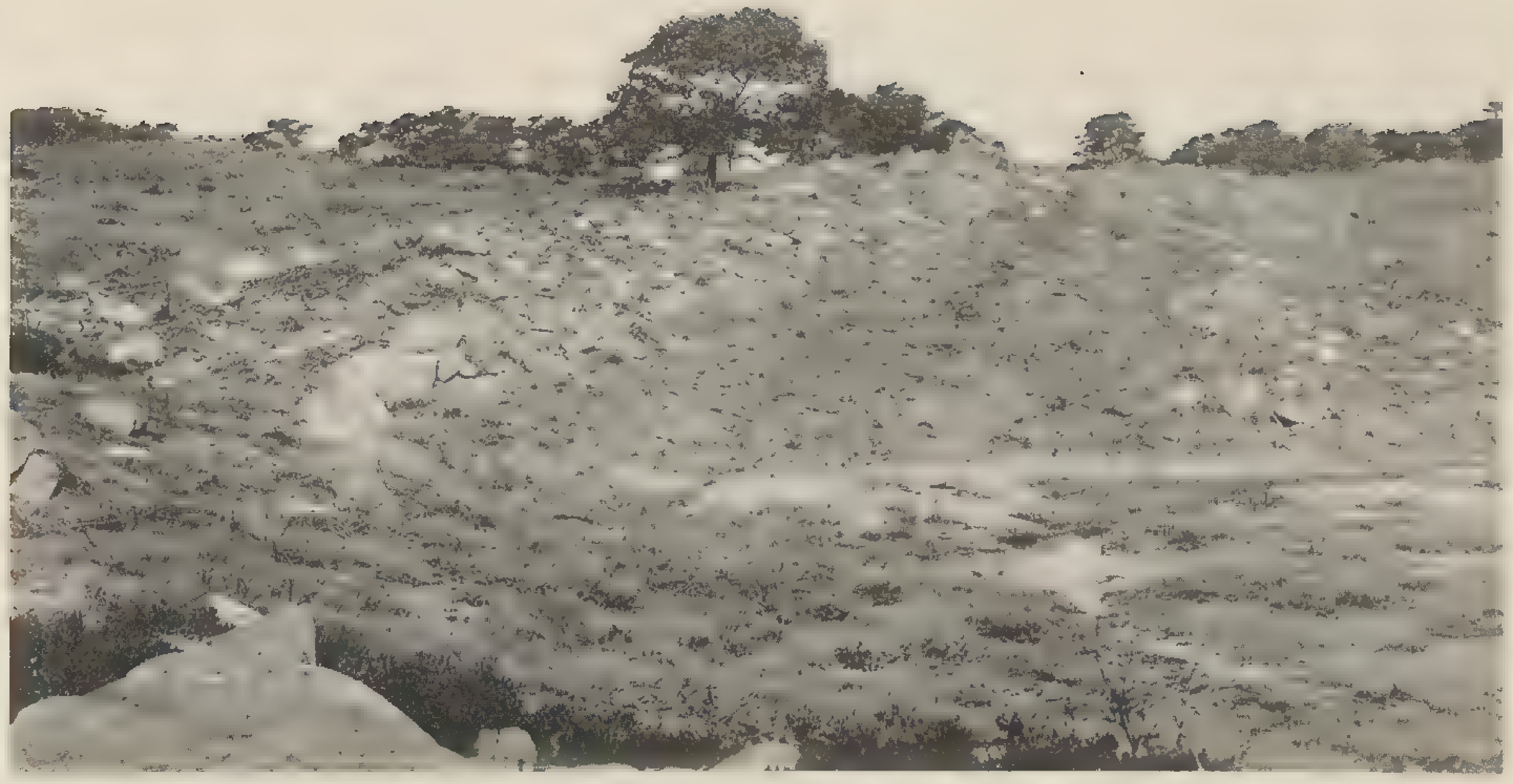
HELIOTYPE CO. BOSTON

PLATE 38

PLATE 38

Geology of Elizabeth Islands

Fig. 1. A shoved frontal moraine on crest of Naushon Island.
Fig. 2. Glacial boulder on beach east of Tarpaulin Cove, Naushon.



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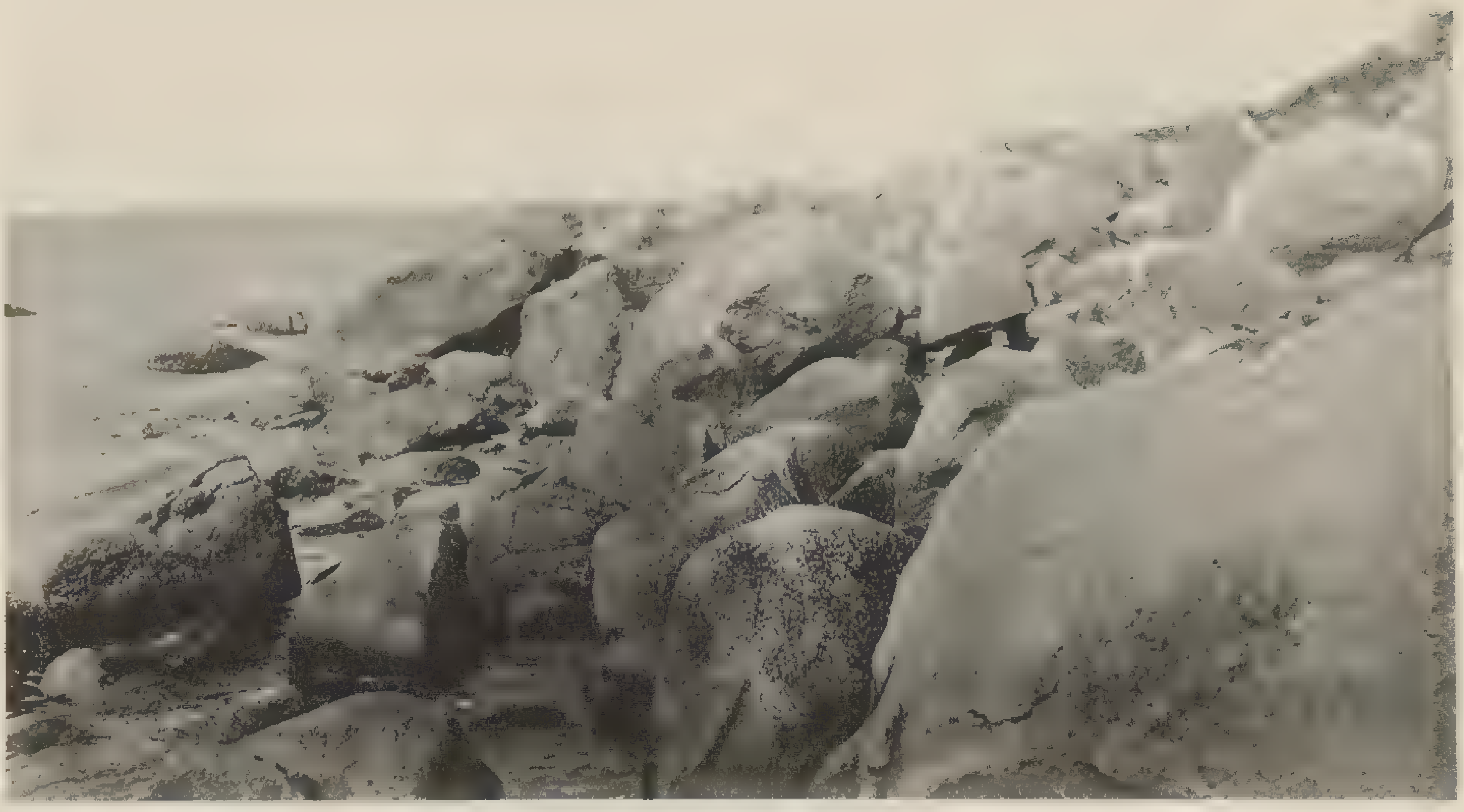

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PUBLICATIONS

OF THE

MUSEUM OF COMPARATIVE ZOÖLOGY

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There have been published of the Bulletin Vols. I to LXV, Vols. LXVII–LXXV; of the Memoirs, Vols. I to LII.

Vol. LXVI, of the Bulletin, and Vol. LIII of the Memoirs, are now in course of publication.

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